UTILIZATION OF HARDWOODS GROWING ON SOUTHERN PINE SITES

Peter Koch
Southern Forest Experiment Station

Agriculture Handbook No. 605
Volume I of three volumes:
I The Raw Material
II Processing
III Products and Prospective

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Koch, P. 1985. Utilization of hardwoods growing on southern pine sites. U.S. Dep. Agric. For. Serv., Agric. Handb. 605 3710 p.3 vol. U.S. Govt. Print. Off., Washington, D.C.

This three-volume text characterizes the 22 principal hardwood species that grow among southern pines, describes the processes by which they are converted to products, describes present and potential products, analyzes the economic feasibility of such conversions, and discusses trends.

KEYWORDS: Hardwoods, low-grade hardwoods, southern hardwoods, forest resources, Southern States, anatomy, physical properties, specific gravity, moisture content, chemical analysis, extractives, mechanical properties, logs, low-grade logs, small logs, grades, log grades, tree grades, yield, defects, insects, fungi residues, harvesting residues, bark, roots, leaves, utilization, complete tree utilization, complete tree harvesting, complete tree chipping, chipping, harvesting, debarking, drying, machining, bending of wood, steam bending, preservation, preservative treatment, pressure treatment, lumber, fiberboard, particleboard, structural particleboard, pulp, paper, energy sources, chemical utilization, economics, *Fraxinus pennsylvanica*, *Fraxinus americana*, *Ulmus americana*, *Ulmus alata*, *Celtis* spp., *Carya cordiformis*, *Carya tomentosa*, *Carya glabra*, *Carya ovata*, *Acer rubrum*, *Quercus velutina*, *Quercus marilandica*, *Quercus falcata*, var. *pagodaefolia*, *Quercus prinus*, *Quercus laurifolia*, *Quercus rubra*, *Quercus stellata*, *Quercus coccinea*, *Quercus shumardii*, *Quercus falcata* var. *falcata*, *Quercus nigra*, *Quercus alba*, *Magnolia virginiana*, *Liquidambar styraciflua*, *Nyssa sylvatica*, *Liriodendron tulpifera*.

THE AUTHOR

Peter Koch is one of America's most eminent scientists in wood technology.

After gaining early experience in the design and manufacture of heavy-duty planers and matchers, he spent a year studying the effects of chip formation on cutterhead horsepower and quality of surfaces generated in peripheral milling. His Ph.D. thesis, accepted by the University of Washington in 1954, contained high-speed photos of chips forming under the action of knives and was basic to later work on the chipping headrig.

After 2 years of teaching and research at Michigan State University and 5 years of managing a New England lumber company, he wrote the book *Wood Machining Processes*.

From 1963 through 1982, Koch headed the Southern Forest Experiment Station's timber utilization laboratory at Pineville, Louisiana. Here, in 1963, he cooperated with two machine manufacturers to develop three versions of chipping headrigs, which square logs by converting the round sides into pulp chips, creating no slabs and wasting no material as sawdust. They are now in wide industrial use throughout North America and comprise one of the major wood-machining advances of the 20th century.

During 1964, as manufacture of southern pine plywood was being developed, Koch provided data instrumental to the formation of gluing practices for the new industry. Next, he developed a system of gluing up single-species wooden beams with the most limber laminae in the central and the stiffest in the outer, most highly stressed regions. Beams thus assembled are stronger, stiffer, and more uniform than those arranged conventionally. For these three developments he was awarded, in 1968, the Superior Service medal of the U.S. Department of Agriculture.

During this period, Koch invented a widely applied method of drying southern pine 2 by 4 studs in 24 hours while restraining them so they are straight when dry. He also led a team effort, in which his personal research played an important part, in developing a structural flakeboard from mixed southern hardwoods—including 60 percent by weight of dense oaks and hickories; start-up of the first commercial plant using the process is scheduled for 1983.

Koch's widely used two-volume reference text *Utilization of the Southern Pines* was published as Agriculture Handbook 420 in 1972.

In 1973, he developed the concept of severing the lateral roots of trees and then pulling them with central root mass intact for use in the production of energy, pulp and paper, or naval stores; numerous machines employing the concept are in commercial operation. In 1974, he conceived a machine that would clean up logging slash comprised of tops and branches, standing culls, and stumps; through his team leadership the concept was brought to commercial prototype stage in 1978; the residue is retrieved in the form of fuel chips.

Also in 1978, a commercial-scale prototype suspension burner for wet wood and bark, which Koch co-invented, was successfully tested. By 1980, the Abstract Information Digest Service (AIDS) of the Forest Products Research Society, which he initiated, matured as an economically viable computerized information retrieval system for the forest products industry.

In 1972-1973, Koch served as President of the Forest Products Research Society; in 1974 he was elected Fellow in the International Academy of Wood Science, and in 1982 was elected Fellow in the Society of American Foresters. Other recognitions of the esteem in which he is held by his profession include an honorary doctor of science degree from the University of Maine, a John Scott Award, and a Woodworking Digest Award.

Completion of the present three-volume work *Utilization of Hardwoods Growing on Southern Pine Sites* concluded Dr. Koch's Forest Service work in the South. He is currently in Missoula, Montana, with the Intermountain Forest and Range Experiment Station leading research on utilization of lodgepole pine in North America.

ACKNOWLEDGEMENTS

In preparing this 29-chapter, 3-volume work characterizing many species of southern hardwoods in relation to their industrial use, I received essential assistance and services of numerous kinds from many sources. Especially significant contributions were made by the researchers who wrote the papers referred to in chapter front pages and footnotes. Many of these were prepared for five symposia presented by the Southern Forest Experiment Station and the Forest Products Research Society, as follows:

Subject	*Location and date*	*Other cooperators*
• Ultrastructure of wood and wood products	Alexandria, La. Feb. 26-28, 1973	North Central Forest Experiment Station
• Resource analysis of hardwoods on southern pine sites and harvesting methods	New Orleans, La. Nov. 6-7, 1973	—
• Utilization of hardwoods growing on southern pine sites	Alexandria, La. March 10-14, 1975	—
• Complete-tree utilization of southern pine	New Orleans, La. April 17-19, 1978	International Union of Forestry Research Organizations; American Plywood Assoc.; Southeastern Area State and Private Forestry, Forest Service
• Utilization of low-grade southern hardwoods—feasibility of 36 enterprises	Nashville, Tenn. Oct. 6-8, 1980	University of Tennessee, Agricultural Extension Service; Hardwood Research Council; Tennessee Division of Forestry; Southeastern Area State and Private Forestry, Forest Service

To emphasize key sources, each chapter title page carries names of researchers from whose research data in the chapter are principally drawn.

Special acknowledgement is due the more than 100 scientists who meticulously studied and criticized various chapters and sections.

The Abstract Information Digest Service (AIDS) of the Forest Products Research Society was invaluable in locating source material.

Essential library services, and unfailing support and counsel, were supplied by the Southern Forest Experiment Station. Other aid from within the U.S. Department of Agriculture included knowledge and guidance provided by the Forest Service's Division of Forest Products and Engineering Research and by the Forest Products Laboratory at Madison, Wisconsin.

To members of the Forest Products Utilization Research Project at the Alexandria Forestry Center, Pineville, Louisiana, I owe particularly personal thanks. The scientists accelerated their research to fill many gaps in information; the technicians assisted them in ways that often went beyond the call of duty; and the administrative personnel efficiently handled infinite details of correspondence and text. The decade-long meticulous work of Carolyn Davis, who typed the manuscript and validated the citations, is particularly appreciated.

Most of the drawings in the text were drafted by Paul E. Kajor, whose sustained and careful work is gratefully acknowledged.

Finally, George K. Stephenson, applying his extraordinary breadth of knowledge of southern forests and forestry, edited the entire text—earning my respect and appreciation.

Since the book is a digest of all research observations specific to the properties and utilization of hardwoods growing among southern pines, a substantial effort was made to abstract, or make reference to, all major work published prior to 1982. Some findings published or in process during 1982 were also included. Inevitably some worthwhile work has been overlooked; for such omissions, I apologize.

Absence of some tabular entries requires explanation. Missing (unavailable) data are indicated by insertion of a dash (—); blanks in table bodies indicate inapplicability.

On many of the illustrations, negative numbers are indicated; these negatives are filed either at the Forest Products Laboratory, Madison, Wis. (those with prefix M), or in the Office of Information, Audiovisual Group, Photo Library, Washington, D.C. A copy negative of every illustration, enumerated or not, is in Study file FS-SO-3201-5.17 at the Southern Forest Experiment Station, Forest Service, Pineville, La.

Peter Koch
Pineville, La.
June 1982

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PART I—BACKGROUND

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I

Introduction

CHAPTER 1

Introduction

Survey data of 1970 show about 500 million acres of commercial forest land in the 50 states of the United States (U.S. Department of Agriculture, Forest Service 1974, p.8). More than 190 million acres of this total are in the South. Almost 138 million acres, or over 70 percent, of these southern commercial forests are uplands, supporting pine or showing evidence, such as stumps, of the former occurrence of pine (Murphy and Knight 1974). These forests are the "southern pine sites" considered in this book. Not limited to sites where pines are dominant, this definition approximates the land capable of growing pine in the South—a key national resource.

Extensive pine harvests over the past century and fire exclusion in more recent decades have accelerated the natural succession from pine to hardwoods (Bormann 1953; Quarterman and Keever 1962; Smith 1962, p. 415; Daubenmire 1967, p. 230-231; Wenger 1968, p. 91). In the last half-century, natural seeding of abandoned cropland and tree planting by landowners, especially forest industry, have resulted in extensive stands of relatively pure pine. Nonetheless, almost 73 million acres of the 138-million-acre southern pinery are today covered by low-grade hardwoods; where southern pines grow there is nearly 0.8 cubic foot of these hardwoods for every cubic foot of pine (Murphy and Knight 1974).[1]

Virtually all forest economists agree that, in the future, substantially more wood products must be harvested from the southern pineries to meet anticipated needs of the country. To supply future demands, forests on these sites must have higher proportions of the faster growing and more versatile pine. Major opportunities for forest improvement, other than type conversion, are vanishing. Nearly all commercial forests are now protected from fire; further investments in fire protection can add little to growth. Past planting has left little bare land to reforest. Even improvement of genetic stock will have little impact on supply prior to the 1990's. The hardwood component of pine stands now being harvested is thus both a major opportunity and a major problem.

One approach calls for application of present knowledge to deaden, chop, and burn the slower-growing hardwoods and replace them with thrifty faster-growing stands of pine. Such conversion of all acreage occupied by hardwoods would cost several billion dollars (Anderson and Guttenberg 1971; Anderson 1974).

In this environmental age, however, the public rightly objects to the ugliness and waste associated with unutilized debris. Many considerations support a second approach—utilization of hardwoods from pine sites rather than their destruction. Harvest of hardwood trees for manufacture into products would offset part of the outlay for clearing sites for replanting. Also, delaying conversion to pine would no longer drastically raise clearing costs. Moreover, feeding large tonnages of hardwood into the stream of industrial raw material could satisfy some of the anticipated excess demand for southern pine. Finally, the entire economics of harvesting hardwood residuals has changed with the quadrupling of oil costs that occurred in the early 1970's. Harvesting costs, in many cases, approximate fuel values—which creates a threshold value for these residuals.

---

[1] The ratio 1:.753 was computed from survey data developed during preparation of the Murphy and Knight (1974) manuscript.

There are many difficulties in utilizing the hardwood resource on these sites. Typical trees are often scarred and defective from fires and from previous pine harvesting. They are often slow growers because the sites are not right for them—trees 6 inches in diameter at breast height (dbh) are typically 40 years of age (Manwiller 1974). They are small in diameter and both short and crooked in bole. The low cubic content per stem, the highly variable species mix from site to site and from stand to stand, and the low cubic volume per acre all combine to raise harvesting costs. Moreover, their value after harvest is low. Knots and other defects, short lengths and small diameters, preclude any hope of sawing quality lumber in conventional lengths. Not least among the problems is that of maintaining a species mix suitable for a manufacturing operation (Barber 1975).

Offsetting these adverse considerations are some positive factors. One of the major assets of this hardwood resource is its large acreage and its wide distribution throughout the southern pineries. The resource is therefore available in close proximity to a large number of potential consumers. Moreover, the volumes are substantial. They can supply a market of almost any realizable magnitude—and at a variety of locations. There will always be a supply, because on many sites hardwoods replace southern pines in natural succession, and certain sites, such as areas bordering intermittent streams in uplands, will remain in hardwoods for environmental reasons.

Stumpage cost is low, leaving much of the final product value for harvest and manufacture. New industries based on these hardwoods can be located in depressed rural areas with available labor, where local communities welcome plant establishment. Finally, factories utilizing these hardwoods can be energy self-sufficient (Barber 1975).

Improved utilization of hardwoods from pine sites should hasten the time when wood production can be maximized by concentrating hardwood management on sites best suited for these species and pine production on lands best suited for pines. Hardwood sites intermingled with pine lands will permit a desirable pattern of diversity in most areas. Substantial acreages suitable for high production of either hardwoods or pine are available; these lands can be managed for either species group as needed to balance demands, not only for industrial wood products, but also for wildlife habitat, recreational areas, visually pleasing landscapes, and water management.

Advancement of technology for the utilization of hardwoods that grow among southern pines is therefore the ultimate purpose of this book.

The presentation encompasses three major objectives: characterization of these hardwoods as raw material, description of the processes by which they are converted to use, and analyses of products that give promise of being competitive in the marketplace. Information is mainly from three sources: literature on hardwoods dating back to near the turn of the century, research within the last 8 years designed to fill obvious gaps in the literature and to develop new processes appropriate for the resource, and reviews of information germane to the hardwood resource by authorities in selected fields.

The text is not a treatise on utilization of the quality hardwood timber typical of bottomland and cove sites. It is, rather, a presentation of facts pertinent to pine-site hardwoods as a raw material and factors controlling manufacture of this raw material into products. Because of the magnitude of the resource, it emphasizes commodity products felt to be marketable in large tonnages. A vast array of specialty products, saleable in very small tonnages, is not discussed.

Not all subjects are treated in equal depth. For example, the anatomy of key species is presented in considerable detail, as is information on tree biomass, extractives, machining, fiberboards, and structural flakeboard. By contrast, the chapters devoted to physiology and pulping are short; information on physiology and the technology of the pulp and paper industry is too highly developed to be comprehensively digested in a single handbook. Data on gluing, mechanical fastening, and finishing are in chapters describing product manufacture and properties rather than in separate chapters. Omitted here also, is much basic information on manufacturing processes that would duplicate the detailed coverage in Agricultural Handbook 420, *Utilization of the Southern Pines* (Koch 1972).

This book—a companion to Agriculture Handbook 420—is addressed primarily to researchers and resource managers in the southern wood industry. Foremen, superintendents, quality control personnel, wood procurement personnel, forest managers, extension workers, professors, and students of wood technology should all find the handbook of value.

Not completed in time for incorporation in these volumes, but supplemental to them, are three comprehensive reviews on gluing and finishing, as follows:

- Sellers, T.
  Gluing eastern hardwoods—with emphasis on southern hardwoods. (A review intended for 1984 publication in an archival journal; for publication details consult the author, at Mississippi State Forest Products Laboratory, Mississippi State, Miss.)
- Hse, C.-Y.
  Technology of phenolic resins. (A text intended for publication in about 1985 as a General Technical Report of the Southern Forest Experiment Station, U.S. Department of Agriculture, Forest Service, New Orleans, La.)
- Carter, R. (Ed.) 1983.
  Finishing eastern hardwoods. Proceedings No. 7318. Forest Products Research Society, Madison, Wisconsin. 241 p.

All were funded, completely or partially, by the Southern Forest Experiment Station as part of an overall effort to advance the technology for utilization of hardwoods that grow among southern pines.

LITERATURE CITED

Anderson, W. C. 1974. An economist's view of the pine-site hardwood problem. For. Prod. J. 24(4): 14-16.

Anderson, W. C. and S. Guttenberg 1971. Investor's guide to converting southern oak-pine types. U.S. Dep. Agric. For. Serv., Res. Pap. SO-72, 10p.

Barber, J. C. 1975. Utilization of hardwoods growing on southern pine sites—keynote address—liabilities to assets. FPRS Sep. No. MS-75-S58, 4 p. For Prod. Res. Soc., Madison, Wis.

Bormann, F. H. 1953. Factors determining the role of loblolly pine and sweetgum in early old-field succession in the Piedmont of North Carolina. Ecol. Monogr. 23(4):339-358.

Daubenmire, R. F. 1967. Plants and environment: a textbook of plant autecology. 2nd ed. 422 p. New York, N.Y.: John Wiley & Sons, Inc.

Koch, P. 1972. Utilization of the southern pines. U.S. Dep. Agric. For. Serv., Agric. Handb. 420. 1663 p. 2 vol. U.S. Govt. Print. Off., Washington, D.C.

Manwiller, F. G. 1974. Fiber lengths in stems and branches of small hardwoods on southern pine sites. Wood Sci. 7:130-132.

Murphy, P. A. and H. A. Knight 1974. Hardwood resources on southern pine sites. For. Prod. J. 24(7):13-16.

Quarterman, E. and C. Keever 1962. Southern mixed hardwood forest: climax in the southeastern Coastal Plain, U.S.A. Ecol. Monogr. 32(2):167-185.

Smith, D. M. 1962. The practice of silviculture. 7th ed. 578 p. New York, N.Y.: John Wiley & Sons, Inc.

U.S. Department of Agriculture, Forest Service 1974. The outlook for timber in the United States. U.S. Dep. Agric. For. Serv., For. Resour. Rep. 20, 374 p. U.S. Govt. Print. Off., Washington, D.C.

Wenger, K. F. 1968. Silvics and ecology of loblolly-shortleaf pine-hardwood forests. *In* The ecology of southern forests, pp. 91-98. 17th annu. for. symp. Baton Rouge, La.: La. State Univ. Press.

2

The resource

Date drawn principally from research by:
R. C. Beltz
J. F. Christopher and his associates
CORRIM Panel II (Boyd et al. 1976, 1977)
H. A. Knight
P. A. Murphy

CHAPTER 2

The resource

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CHAPTER 2

The resource

In 1970, softwood and hardwood forests of the United States yielded 193 million tons (ovendry basis, including bark) of sawlogs, veneer logs, pulpwood, and miscellaneous industrial wood. By 1985, demand for such wood may be in the range from 248 to 260 million tons; by the year 2000, demand will probably be between 296 and 307 million tons (Boyd et al. 1976, 1977).

Supplying these quantities on a sustained basis will require intensive management of growing forests and utilization of much material that is now wasted.

The pine sites of the South, capable of maximum production when fully stocked with pines, now support about one-fourth of all the hardwood growing stock in the country. Because optimum use of this hardwood can at once increase current harvests and make land available for faster future growth, the hardwood now growing on pine sites constitutes a key element in the Nation's timber resource. Unfortunately, much of this hardwood is in trees of small diameter and low quality in species not readily utilized by conventional methods.

2-1 NATIONAL SUPPLY AND DEMAND FOR HARDWOOD

The most recent statistics on the national hardwood situation (1970) afford background relevant to consideration of the hardwood resource on pine sites. Projected national volume growth and demand data are also pertinent to planning for utilization of wood resources on pine sites.

IN 1970

Hardwoods are a major component of our national timber resource; in 1970, they comprised nearly 40 percent of the total growing stock, as follows (U.S. Department of Agriculture, Forest Service 1974; Boyd et al. 1976, 1977):

	Sawtimber	Pulpwood and pole-size timber	Total
	Million tons, ovendry basis, including bark		
Hardwood	1,554	2,371	3,915
Softwood	4,770	1,740	6,510
Total	6,314	4,111	10,425

The utilization potential of this national hardwood resource is related to its growth, mortality losses, and current use. Figure 2-1 charts a national hardwoods flow trajectory for 1970; that is, a graphic representation of material flow from growing stock of hardwood standing timber to commodity removals in the

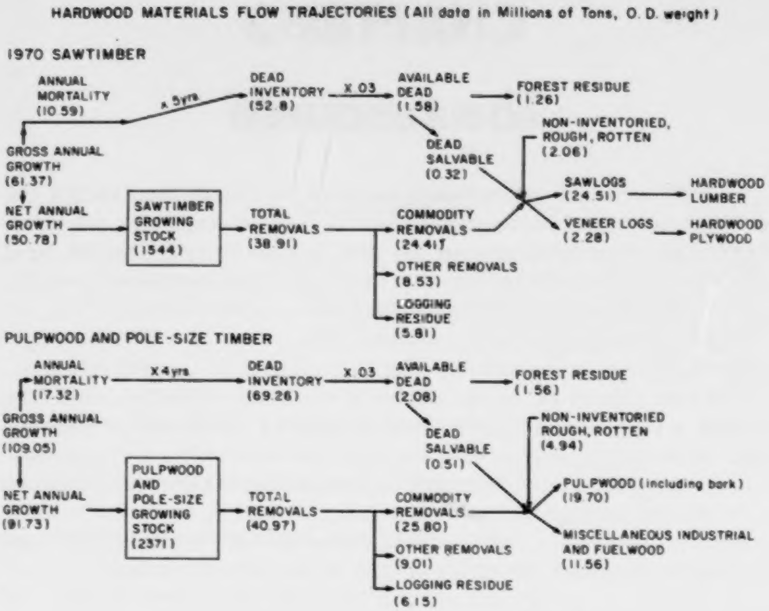
HARDWOOD MATERIALS FLOW TRAJECTORIES (All data in Millions of Tons, O. D. weight)
1970 SAWTIMBER
ANNUAL MORTALITY (10.59)
x 5yrs
DEAD INVENTORY (52.8)
X .03
AVAILABLE DEAD (1.58)
FOREST RESIDUE (1.26)
NON-INVENTORIED, ROUGH, ROTTEN (2.06)
DEAD SALVABLE (0.32)
GROSS ANNUAL GROWTH (61.37)
NET ANNUAL GROWTH (50.78)
SAWTIMBER GROWING STOCK (1544)
TOTAL REMOVALS (38.91)
COMMODITY REMOVALS (24.41)
SAWLOGS (24.51)
HARDWOOD LUMBER
VENEER LOGS (2.28)
HARDWOOD PLYWOOD
OTHER REMOVALS (8.53)
LOGGING RESIDUE (5.81)
PULPWOOD AND POLE-SIZE TIMBER
ANNUAL MORTALITY (17.32)
X 4yrs
DEAD INVENTORY (69.26)
X .03
AVAILABLE DEAD (2.08)
FOREST RESIDUE (1.56)
GROSS ANNUAL GROWTH (109.05)
DEAD SALVABLE (0.51)
NON-INVENTORIED ROUGH, ROTTEN (4.94)
NET ANNUAL GROWTH (91.73)
PULPWOOD AND POLE-SIZE GROWING STOCK (2371)
TOTAL REMOVALS (40.97)
COMMODITY REMOVALS (25.80)
PULPWOOD (including bark) (19.70)
MISCELLANEOUS INDUSTRIAL AND FUELWOOD (11.56)
OTHER REMOVALS (9.01)
LOGGING RESIDUE (6.15)

Figure 2–1.—1970 materials flow trajectories for hardwood sawtimber (top) and hardwood pulpwood and pole-size timber (bottom) in the United States. Data are principally from *Outlook for Timber in the United States* (U.S. Department of Agriculture, Forest Service 1974). Conversion of cubic feet to ovendry tons has been through multiplication by 0.0164. Data on growth and removals reflect 1970 inventory standards and include bark estimated at 10 percent of wood tonnage. (Drawing after Boyd et al. 1976.)

form of sawlogs, veneer logs, pulpwood, miscellaneous industrial wood, and fuelwood. It also charts non-commodity removals—principally logging residues, and natural mortality leading to dead trees in the inventory, some of which are salvable. The statistics are largely from *The Outlook for Timber in the United States* (U.S. Department of Agriculture, Forest Service 1974).

Data on growth and removals reflect current inventory standards; tonnages do not, therefore, add up to total biomass. Complete tree utilization would permit about 35-percent greater commodity recovery, principally as pulp chips and fuel (Keays 1971).

Net hardwood growth in 1970, 143 million tons (ovendry basis), substantially exceeded harvest removals, 80 million tons. The 80 million tons removed from growing stock, plus 0.8 million tons of dead salvable timber and 7.0 million tons of non-inventoried rough or rotten timber yielded 58 million tons of sawlogs, veneer logs, pulpwood, miscellaneous industrial wood, and fuelwood as follows:

Commodity	Barky roundwood consumed
	-----Million tons, ovendry-----
Hardwood Lumber	24.51
Hardwood plywood	2.28
Paper, paperboard, and fiber panels	19.70
Miscellaneous industrial wood and fuel	11.56
Total	58.05

During conversion of these 58 million tons of roundwood, substantial quantities of by-products, i.e., chips, shavings, trim ends, and bark were produced and incorporated into paper, fiberboard, particleboard, and fuel.

The national inventory of hardwoods includes trees 5 inches and larger in diameter at breast height (dbh). Nearly 90 percent of the 1970 hardwood inventory volume was in trees under 15 inches in dbh, and about half the volume was in trees 6 to 10 inches in dbh (Josephson 1974). These sizes limit the manner in which the national hardwood resource can be utilized; they also influence our international trade. Once a substantial exporter of hardwood, the United States in 1972 went abroad for hardwood plywood and veneer amounting to 4.2 million tons, roundwood equivalent; additionally 1.1 million tons, rondwood equivalent, was imported as lumber; and pulp products amounting to 1.6 million tons (ovendry) roughwood equivalent were imported (U.S. Department of Agriculture, Forest Service 1974, p. 322). Expanding world timber trade and scarcity of large-diameter domestic hardwoods of high quality indicate further increases in imports. Although increasing in absolute terms, imports in the future will perhaps continue at about the same percentage of total hardwood consumption in the United States.

In 1970, there was a 63-million-ton surplus of hardwood net annual growth over removals—mostly in small-diameter trees. This contrasts with the situation for softwoods, where a net surplus of only 15 milllion tons was made up of a deficit of 14 million tons in sawlog sizes, offset by a surplus of 29 million tons in smaller trees (Boyd et al. 1976, 1977).

Innovative and improved utilization of hardwoods can relieve some anticipated shortages of structural softwood products; moreover, removal of the hardwoods can permit expansion of softwood forest areas to provide a better balance between supply and demand for both species groups—now and in the future.

IN 2000

Projections for the year 2000 (Boyd et al. 1976, 1977) assume a trend toward substitution of products from plentiful small hardwoods for softwood products in short supply. Even so, growth and harvest of hardwood can be in approximate balance (fig. 2-2); a shift in southern forests from low-grade hardwoods to southern pine need not cause future hardwood shortages, and such a shift may be essential to balancing future pine growth with projected needs.

In assessing trends, it is recognized that trees available for future harvest will, on the average, be smaller and that there will be both economic and social

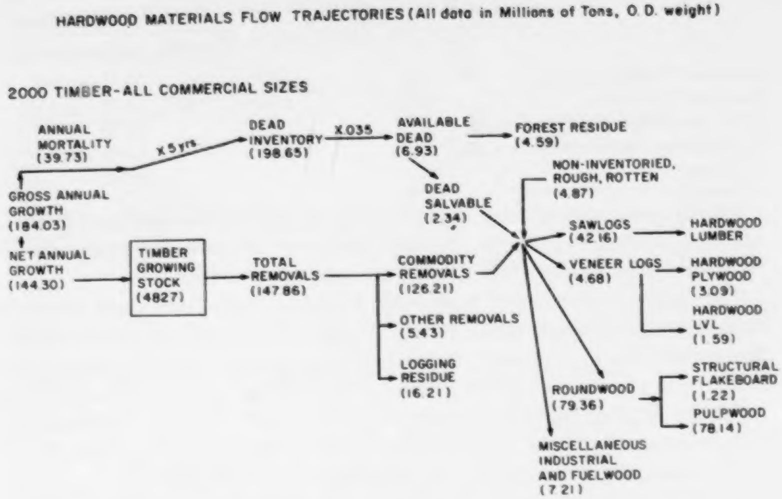
HARDWOOD MATERIALS FLOW TRAJECTORIES (All data in Millions of Tons, O. D. weight)
2000 TIMBER-ALL COMMERCIAL SIZES
ANNUAL MORTALITY (39.73)
X 5 yrs
DEAD INVENTORY (198.65)
X.035
AVAILABLE DEAD (6.93)
FOREST RESIDUE (4.59)
NON-INVENTORIED, ROUGH, ROTTEN (4.87)
GROSS ANNUAL GROWTH (184.03)
DEAD SALVABLE (2.34)
SAWLOGS (42.16)
HARDWOOD LUMBER
NET ANNUAL GROWTH (144.30)
TIMBER GROWING STOCK (4827)
TOTAL REMOVALS (147.86)
COMMODITY REMOVALS (126.21)
VENEER LOGS (4.68)
HARDWOOD PLYWOOD (3.09)
HARDWOOD LVL (1.59)
OTHER REMOVALS (5.43)
LOGGING RESIDUE (16.21)
ROUNDWOOD (79.36)
STRUCTURAL FLAKEBOARD (1.22)
PULPWOOD (78.14)
MISCELLANEOUS INDUSTRIAL AND FUELWOOD (7.21)

Figure 2-2.—Hardwood materials flow trajectory projected for the year 2000 in the United States. Data are principally from U.S. Department of Agriculture, Forest Service (1974). Conversion of cubic feet to ovendry tons has been through multiplication by 0.0164. Data on growth and removal reflect 1970 inventory standards and include bark estimated at 10 percent of wood tonnage. (Drawing after Boyd et al. 1976.)

pressures for complete utilization of all stems. Improved precision sawing and improved planing of hardwoods will significantly raise lumber recovery from each cubic foot of log, but average lumber grade will decrease. Also, it is likely that wood in a variety of composite and reconstituted forms will be increasingly used for structural products, thereby improving the degree of use substantially.

These trends point to less distinction in future use and value between sawlog and smaller timber than at present. In developing a materials flow trajectory (materials balance) for the year 2000, Boyd et al. (1976) pooled all hardwood timber in commercial sizes (5-inch dbh and larger to a 4-inch top outside bark). The projection (fig. 2-2) shows that hardwood removals (148 million tons) will be less than the gross annual growth that year (184 million tons), but slightly more than the net annual growth (144 million tons) after deduction for annual mortality (40 million tons). By 2000, the hardwood growing stock inventory of 4,827 million tons will be substantially greater than the 1970 inventory of 3,915 million tons.

In the year 2000, therefore, the 147.86-million-ton removals from hardwood growing stock, together with 7.21 million tons of dead salvable hardwood and non-inventoried rough and rotten timber will yield 133.41 million tons of sawlogs, veneer logs, roundwood, and miscellaneous industrial fuel wood about as follows:

Commodity	Barky roundwood consumer
	-----Million tons, ovendry-----
Sawlogs for lumber	42.16
Veneer logs for plywood	3.09
Veneer logs for lumber laminated from veneer	1.59
Roundwood for structural flakeboard	1.22
Roundwood for pulp and fiberboard	78.14
Miscellaneous industrial wood and fuelwood	7.21
Total	133.41

As in 1970, these tonnages of logs will additionally yield by-products of chips, shavings, and trim ends for incorporation into paper, fiberboard, and particleboard. Bark will find use as fuel, mulch, and a spectrum of more sophisticated products.

Hardwood supplies will probably be adequate to meet most national demands, but traditional product mixes will be considerably altered. Thus, high-grade veneer and solid hardwood lumber in desired sizes will be in short supply, but important new classes of reconstituted products such as medium-density fiberboard (Suchsland and Woodson 1976), structural flakeboard (Hse et al. 1975), dowel-laminated crosties (Howe and Koch 1976), and lumber laminated from veneer (Koch 1973) will appear in the market place to satisfy our national demands for wood products.

2-2 THE SOUTHERN HARDWOOD RESOURCE

To this point, data discussed relate to the hardwood resource of the entire United States. The outlook study (U.S. Department of Agriculture, Forest Service 1974, p. 46 and 55) notes that in 1970, of a total national hardwood growing stock of 217 billion cubic feet of wood (3,915 million tons of wood and bark, overndry), the 12 Southern States listed in table 5 contained 81.1 billion cubic feet of wood (1,463 million tons of wood and bark, ovendry) or about 37 percent.

Murphy and Knight (1974) estimated the southern hardwood resource at 108.3 billion cubic feet of wood (1,954 million tons of wood and bark, ovendry) in trees 5 inches or larger in diameter at breast height. Information assembled by the staff of the Renewable Resources Evaluation Work Unit of the Southern Forest Experiment Station (Christopher et al. 1976), based on source data gathered from 1964 to 1974, indicates a total hardwood resource in the 12 Southern States of 113.7 billion cubic feet (in trees 5 inches dbh and larger, to a 4-inch top, measured outside bark); this amounts to 2,051 million tons of wood and bark, ovendry.

Each of these three estimates of southern hardwood volume reflected the most current survey data available at the time of writing. The outlook study is the oldest, and that by Christopher et al. (1976) the most recent. The trend of these estimates tends to confirm a continuing increase in the southern hardwood resource, and that the south will continue to be a major source of supply.

Murphy and Knight (1974) and Christopher et al. (1976) have inventoried the hardwood resource of the 12 Southern States listed in table 5 in two broad categories—that on pine sites and that on hardwood sites. Both estimate more than 40 percent of the total on pine sites, the former estimating the pine site hardwoods at 54.0 billion and the latter at 49.2 billion cubic feet of wood. These estimates are equivalent to 974 and 888 million tons of wood and bark (ovendry basis), respectively.

2-3 DEFINITION OF SOUTHERN PINE SITES

For the purposes of this text, pine sites are defined as forested uplands, excluding those growing cove-type hardwoods, that are supporting southern pine or show evidence, like stumps, of its former occurrence. This definition excludes alluvial lands and "branch-bottoms" wider than 132 feet recognized as wet alluvial and colluvial areas along small intermittent or perennial streams, all of which are classed as hardwood sites. It limits pine sites, as closely as any broad site classification can, to lands on which pines grow faster and attain better form than do hardwoods. With few exceptions, these are lands better suited for pine production, and the occurrence of hardwoods on them indicates less than optimum economic use.

As noted in chapter 1, this definition encompasses 138 million acres in the 12 Southern States. How did the southern pines come to occur on more than 70 percent of southern commercial forest land? First, pines are among the older existing land plants; they antedate most broad-leaved species. Second, by their ability to withstand intense illumination and dry environments and by their modes of reproduction and dissemination, the pines are characteristically pioneer invaders of newly exposed land surfaces (Bormann 1953; Quarterman and Keever 1962; Mirov 1967). Throughout their range, pines are capable of surviving on a wide range of sites and are adapted to occupy disturbed sites where ecological succession has been interrupted. In recorded history, there have always been enough disturbances to keep pines on a large part of southern lands. Pine stands were widespread when Europeans arrived on this continent and their extent was determined more by local disturbance history than by site characteristics. Pine sites, i.e., lands capable of growing pines, very likely cover much more area than was in pine in 1492.

In today's southern pine region, the southern pines occupy some of the most ancient (225-million-year-old) and some of the most recent (less than 1,000-year-old) land surfaces in the United States. Readers wishing to delve into the geologic history of southern pine sites will find Wakeley's (1969) review of interest.

2-4 SPECIES SUCCESSION ON PINE SITES

How is it, that the pine sites have become so heavily invaded by hardwoods? Replacement of pines by hardwoods is partly the result of successional trends unchecked by fire. In most of the South, plant succession—the replacement of one plant community with another—climaxes with a hardwood forest (Billings 1938; Quarterman and Keever 1962). Establishment of pine stands requires the absence of heavy litter and freedom from competing plant cover. These conditions were present when the large-scale abandonment of farmland in the South permitted thousands of acres to be naturally seeded to pine (Murphy and Knight 1974). Also, much pine became established on vast acreages of cutover land; such establishment was frequently aided by fires that suppressed competition.

Disturbed areas, old fields, cutovers, fire swathes, and tornado strips are first occupied by annual weeds and sedge grasses; pine establishment follows immediately, or at least within 5 years, depending on seed availability (Oosting 1942; Bormann 1953).

Once stands close, 10 to 15 years after establishment, pines are unable to perpetuate themselves in their own shade; several hardwood species are able to invade shady pine stands, however. As a consequence, barring periodic fires, a middle-aged (40-year-old) pine stand will have a distinct understory of hardwoods. Pines 75 years of age are apt to be overmature, and as they thin out they are replaced by hardwoods that have steadily increased in the lower strata. Eventually (after 150 to 200 years) hardwood dominance—principally oaks and hickories—will be attained with scattered pines remaining as relicts (Bormann 1953).

Fitzgerald et al. (1973) noted that many upland southern pine sites in hilly areas, if totally undisturbed by natural or human-caused forces, would develop to decaying, degenerate, open stands of hickory (*Carya sp.* Nutt.) and oak (*Quercus sp.* L.) with a beech (*Fagus grandifolia* Ehrh.) component on the middle and lower slopes. The deterioration of these stands would be accompanied by the gradual establishment of tolerant scrubby species such as hophornbeam (*Ostrya virginiana* (Mill.) K. Koch), blue beech (*Carpinus caroliniana* Walt.), and other similar species with no commercial or recreational values. Similar succession in the Coastal Plain would result in site occupation of the sand ridges by the scrub oaks: turkey oak (*Q. laevis* Walt.), bluejack oak (*Q. incana* Bartr.), and scrubby post oak (*Q. stellata* var. *margaretta* (Ashe) Sarg.). Moist sites would revert to a cover of gallberry (*Ilex glabra* (L.) Gray)— and wax Myrtle (*Myrica cerifera* L.).

In the course of development of a pine stand, the hardwood component increases with time. Hardwood volumes can be relatively low and unimportant at pulpwood age, but at age 70 the competing hardwoods are generally taller and more numerous. A key time, but not the only time, to control the hardwood growth is when the stand is harvested and regenerated.

The trend from pine to hardwood is not inevitable. In some areas, natural wildfire has maintained pine supremacy; the longleaf pine (*Pinus palustris* Mill.) forest of the Coastal Plain is a prime example (Croker 1969). Prescribed fire can be used to control successional trends, but to date only about 14 percent of the prescribed burning in the South has been for hardwood control (Hough 1972-73).

Control of competing hardwoods, although widely practiced, is beyond the scope of this book, whose aim is better utilization of hardwoods.

2-5 THE HARDWOOD SPECIES ON PINE SITES

Of the total hardwood volume standing on southern pine sites, about 90 percent is in 23 species or species groups representing 10 genera, as follows:

Common Name	Botanical Name
Ash, green	*Fraxinus pennsylvanica* Marsh.
Ash, white	*F. americana* L.
Elm, American	*Ulmus americana* L.
Elm, winged	*U. alata* Michx.
Hackberry	*Celtis* spp.
Hickory	*Carya* spp.
Maple, red	*Acer rubrum* L.
Oak, black	*Quercus velutina* Lam.
Oak, blackjack	*Q. marilandica* Muenchh.
Oak, cherrybark	*Q. Falcata* Michx. var. *pagodaefolia* Ell.
Oak, chestnut	*Q. prinus* L.
Oak, laurel	*Q. laurifolia* Michx.
Oak, northern red	*Q. rubra* L.
Oak, post	*Q. stellata* Wangenh.
Oak, scarlet	*Q. coccinea* Muenchh.
Oak, Shumard	Q. shumardii Buckl.
Oak, southern red	*Q. falcata* Michx. var. *falcata*
Oak, water	*Q. nigra* L.
Oak, white	*Q. alba* L.
Sweetbay	*Magnolia virginiana* L.
Sweetgum	*Liquidambar styraciflua* L.
Tupelo, black	*Nyssa sylvatica* Marsh.
Yellow-poplar	*Liriodendron tulipifera* L.

Because chestnut oak volume is negligible in five states (Arkansas, Florida, Louisiana, Oklahoma, and Texas), it was not realized until the Christopher et al. (1976) data were in hand, that this species accounts for 2.9 percent of the hardwood volume on pine sites. For this reason, chestnut oak was not included in F. G. Manwiller's Southwide collection in 1972 of the hardwood species (see U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Study FS-SO-3201-1.38); data on chestnut oak are therfore missing or incomplete in some of the tables and discussions characterizing hardwoods on pine sites.

2-6 SURVEY DATA

Survey data specific to hardwoods on pine sites have been summarized by region and state, respectively, by Murphy and Knight (1974) and Christopher et al. (1976). Data were primarily gathered by on-the-ground measurement of trees on sample plots between 1964 and 1974 by Renewable Resources Evaluation Work Units of the Southern and Southeastern Forest Experiment Stations of the Forest Service. Volumes are expressed in cubic feet, inside bark, of trees from stump to minimum 4-inch top diameter (outside bark) of central stem. All trees 5 inches in diameter at breast height and larger are included. Sampling error of these surveys is least for Southwide data on cubic volume (on the order of plus or minus 1-½ percent, but is substantially greater for data broken down by site and species.

Because the two analyses are not based on identical survey years, the summary statistics from them differ slightly—but not in any important way. The data from Christopher et al. (1976) reflect new inventories of Louisiana and North Carolina.

REGIONAL ANALYSIS[1]

In the Murphy and Knight (1974) analysis, the southern states were grouped into four regions: West Gulf, Central Gulf, East Gulf, and South Atlantic. Within the regions, two main land types occur: Coastal Plain and Highlands (fig. 2-3).

As noted previously, more than 190 million acres in the South are available for and capable of growing commercial crops of timber. Almost 138 million acres, or 72 percent of this land, are southern pine sitres (table 2-1). The natural

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[1] With some editorial changes, this subsection is taken from Murphy and Knight (1974) by permission of the authors and the Forest Products Research Society.

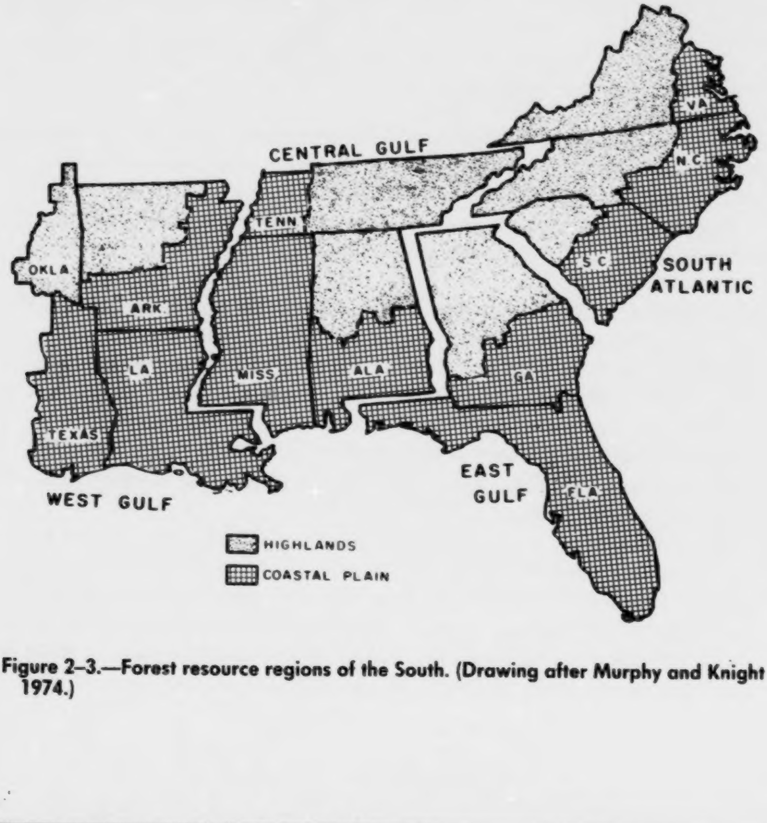

Figure 2-3.—Forest resource regions of the South. (Drawing after Murphy and Knight 1974.)

ranges of the major pines cover virtually all the South, except for some mountainous areas, bottomlands, and northern sections of the region (Sternitzke and Nelson 1970). It is, therefore, not surprising that such large proportions of forest lands in the South are potential pine sites.

The proportion of forest area in pine sites ranges from a high of 80 percent for the South Atlantic to a low of 65 percent for the West Gulf Region. Most of the forest land in the South Atlantic Region is in either the Coastal Plain or the Piedmont. The occurrence of the bulk of the Mississippi River bottom-land hardwood forest west of the river reduces the proportion of pine sites in the West Gulf Region.

Although the acreage in pine sites indicates the amount of land that can support southern pine, it does not provide any clues as to the amount actually occupied by either pine or hardwoods. However, forest types do.

TABLE 2-1.—*Area of commercial forest land in the South, by site* (Murphy and Knight 1974)

Region	Site		All
	Pine	Hardwood	sites
	Thousand acres		
South Atlantic	38,596	9,651	48,247
East Gulf	31,015	10,056	41,071
Central Gulf	35,428	15,617	51,045
West Gulf	32,891	17,625	50,516
All regions	137,930	52,949	190,879

Murphy and Kight (1974) combined the main forest types on pine sites into three groups: pine—50 percent or more in pine; pine-hardwood—25 to 49 percent in pine; and hardwood—50 percent or more in hardwoods.

Pine forest types occupy 65 million acres, or slightly less than half the South's pine sites (table 2-2). Pine also accounts for a significant portion of the stocking on the 31 million acres occupied by the pine-hardwood type. On the remaining 42 million acres suitable for pine, oak-hickory is the prevailing forest type.

The proportion of pine forests is highest in the East Gulf, where two-thirds of the pine site acreage is in pine types. Each of the 10 southern pine species is indigenous to the East Gulf. Furthermore, one out of every three acres of artificial planting or seeding in the South has been in this region.

About 54 billion cubic feet, or half the South's hardwood inventory, occurs on pine sites (table 2-3). This total is the volume of sound wood in trees 5 inches or larger in diameter at breast height.

The proportion of the hardwood inventory that is on pine sites varies by region. It is greatest in the South Atlantic (63 percent), because of a low proportion of hardwood sites and high hardwood volumes on pine sites. The latter may reflect the large amount of the South Atlantic's forest area in the Piedmont, where the successional tendency to hardwood is strong. In the other three regions, 41-to 47 percent of the hardwood is on pine sites. Hardwood density on pine sites is highest, 560 cubic feet per acre, in the South Atlantic Region; the Gulf Central, West Gulf, and East Gulf Regions average 396, 326, and 250 cubic feet per acre, respectively.

Because growing conditions for hardwoods are poor on pine sites, most of the volume is in small stems (table 2-4). About 46 percent is in trees less than 11 inches in diameter.

TABLE 2-2.—*Area of commercial forest land on pine sites by forest type* (Murphy and Knight 1974)

Region	Forest Type			All types
	Pine	Pine-hardwood	Hardwood	
	Thousand acres			
South Atlantic	15,420	8,231	14,945	38,596
East Gulf	20,487	5,812	4,716	31,015
Central Gulf	14,116	8,972	12,340	35,428
West Gulf	15,280	7,969	9,462	32,891
All regions	65,303	30,984	41,643	137,930

TABLE 2-3.—*Volume of all hardwood in the South, by site* (Murphy and Knight 1974)

Region	Site		All sites
	Pine	Hardwood	
	Million cubic feet		
South Atlantic	21,568	12,776	34,344
East Gulf	7,679	10,781	18,460
Central Gulf	14,016	15,540	29,556
West Gulf	10,713	15,233	25,946
All regions	53,976	54,330	108,306

TABLE 2-4.—*Volume of all hardwood on pine sites by diameter* (Murphy and Knight 1974)

Region	Diameter (inches at breast height)			All Sizes
	5.0-10.9	11.0-14.9	15.0+	
	Million cubic feet			
South Atlantic	9,588	6,085	5,895	21,568
East Gulf	3,733	2,043	1,903	7,679
Central Gulf	6,655	4,181	3,180	14,016
West Gulf	4,710	3,226	2,777	10,713
All regions	24,686	15,535	13,755	53,976

To conclude this summary by region, it is useful to tabulate (for comparison with table 2-3) the volume of southern pine growing on pine sites, by region, as follows:

Region	Southern pine on pine sites
	Million cubic feet
South Atlantic	17,010
East Gulf	18,479
Central Gulf	17,819
West Gulf	18,330
All regions	71,638

Thus, the Forest Survey estimates, on pine sites, .753 cubic foot of hardwoods for every cubic foot of southern pine, i.e., 53,976/71,638 = .753.

STATE ANALYSIS[2]

The locations of the South's 138 million acres of pine sites are listed by states in the table 2-5, together with the acreage of hardwood sites and total commercial forest in each state. The acreage of forest types constituting the area of pine site in each state of the South is shown in table 2-6.

Five states each have more than 12 million acres of pine site. Georgia leads with 19.5 million, followed in order by Alabama, North Carolina, Virginia, and Mississippi. In all states except Tennessee and Oklahoma the area of pine site greatly exceeds that of hardwood site.

Georgia also leads in area of pine type—land growing pines with only minor amounts of hardwood—but Florida, Alabama, and North Carolina are next in order. Louisiana, Mississippi, South Carolina, and Texas all have over 5 million acres of pine type. All 12 States have more than 1 million acres of hardwood type on pine sites—Virginia has more than 8 million. Except for Oklahoma, all have over 1 million acres now growing mixed pine-hardwood stands. Together, the hardwood and pine-hardwood acreages reflect the extent of stands in which hardwoods are available for utilization from pine sites.

Tables 2-7 through 2-18 are taken from Christopher et al. (1976); they present for each state, the estimated cubic footage of each of 21 hardwood species and species groups; volumes on pine sites and hardwood sites are shown separately, as are total volumes. Because they are based, in part, on more recent statistics, the data in these tables vary somewhat from those summarized in tables 2-3 and 2-4.

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[2] Data for this subsection are largely from Christopher et al. (1976), by permission of the authors.

State total volumes of hardwoods on pine sites vary from a low of 633 million cubic feet in Oklahoma to a high of 6,838 million in North Carolina, as follows:

State	Hardwood Volume
	Million cubic feet
Oklahoma	633
Florida	1,078
Texas	2,593
Louisiana	3,085
South Carolina	3,358
Tennessee	3,724
Mississippi	3,827
Arkansas	4,926
Virginia	6,118
Alabama	6,456
Georgia	6,600
North Carolina	6,838

Species volumes on pine sites in the 12 Southern States are as follows (from tables 2-7 through 2-18):

Species	Volume	Proportion of pine site hardwood volume
	Million cubic feet	*Percent*
Sweetgum	6,508	13.2
Oak, white	6,058	12.3
Hickory, spp.	4,173	8.5
Oak, southern red	3,994	8.1
Oak, post	3,444	7.0
Yellow-poplar	3,421	7.0
Tupelo, black	2,710	5.5
Oak, water	2,332	4.7
Oak, chestnut	2,102	4.2
Oak, black	1,949	4.0
Oak, scarlet	1,799	3.6
Maple, red	1,751	3.6
Oak, northern red	1,169	2.4
Oak, laurel	683	1.4
Elm, spp.	668	1.4
Oak, cherrybark	579	1.2
Ash, spp.	441	.9
Sweetbay	300	.6
Oak, Shumard	120	.2
Hackberry, spp.	57	.1
Other hardwoods	4,978	10.1
Total hardwoods	49,236	100.0

The listed oaks comprise 47.8 percent of the 12-State volume of hardwoods on pine sites. Sweetgum and white oak are the leading species, each with an inventory of more than 6 billion cubic feet. The hickories, third in abundance, are widespread, though on pine sites their quality tends to be poor.

The five most abundant pine-site hardwoods, sweetgum, white oak, hickory, southern red oak, and post oak, and the seventh, black tupelo, are well represented in all 12 states. Yellow-poplar, scarlet oak, and chestnut oak are scarce or absent west of the Mississippi and in Florida. Black oak is plentiful except in Florida, Texas, Louisiana, and Oklahoma. Among other species making up 2 percent or more of the hardwood on pine sites, red maple is well distributed except in Oklahoma; water oak is scarce only in Tennessee and Oklahoma; and northern red oak is scarce in the Gulf States.

TABLE 2-5.—*Area of commercial forest land, by state and site*
(Data from Renewable Resources Evaluation Work Units of the Southern and Southeastern Forest Experiment Stations, Forest Service)

State	Site		All
	Pine	Hardwood	sites
	Thousand acres		
Alabama	17,357	3,976	21,333
Arkansas	11,570	6,637	18,207
Florida	11,427	4,805	16,232
Georgia	19,588	5,251	24,839
Louisiana	9,365	6,671	16,036
Mississippi	12,158	4,734	16,892
North Carolina	15,389	4,638	20,027
Oklahoma	2,690	2,127	4,817
South Carolina	9,566	2,845	12,411
Tennessee	5,913	6,907	12,820
Texas	9,266	2,190	11,456
Virginia	13,641	2,168	15,809
The South	137,930	52,949	190,879

TABLE 2-6.—*Area of pine site, by state and forest type*
(Data from Renewable Resources Evaluation Work Units of the Southern and Southeastern Forest Experiment Stations, Forest Service)

Region	Forest Type			All
	Pine	Pine-hardwood	Hardwood	types
	Thousand acres			
Alabama	7,638	4,683	5,036	17,357
Arkansas	3,646	2,976	4,948	11,570
Florida	8,199	1,669	1,559	11,427
Georgia	12,288	4,143	3,157	19,588
Louisiana	5,624	2,102	1,639	9,365
Mississippi	5,479	3,124	3,555	12,158
North Carolina	6,986	3,557	4,846	15,389
Oklahoma	795	664	1,231	2,690
South Carolina	5,513	2,137	1,916	9,566
Tennessee	999	1,165	3,749	5,913
Texas[1]	5,215	2,227	1,824	9,266
Virginia	2,921	2,537	8,183	13,641
The South	65,303	30,984	41,643	137,930

[1] Excludes post oak region

TABLE 2-7.—*Volume of all hardwoods on pine sites, Alabama* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	Million cubic feet		
Ash, spp.	276	53	223
Elm, spp.	221	68	153
Hackberry, spp.	143	8	135
Hickory, spp.	1,152	850	302
Maple, red	162	126	36
Oak, black	293	255	38
cherrybark	127	43	84
chestnut	344	284	60
laurel	210	95	115
northern red	155	105	50
post	406	381	25
scarlet	193	166	27
Shumard	45	25	20
southern red	646	602	44
water	743	379	364
white	782	633	149
Sweetbay	332	82	250
Sweetgum	1,612	950	662
Tupelo, black	671	323	348
Yellow-poplar	633	419	214
Other hardwoods	1,740	609	1,131
Total hardwoods	10,886	6,456	4,430

TABLE 2-8.—*Volume of all hardwoods on pine sites and hardwood sites, Arkansas* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	Million cubic feet		
Ash, spp.	283	50	233
Elm, spp.	380	102	278
Hackberry, spp.	244	5	239
Hickory, spp.	1,197	518	679
Maple, red	107	41	66
Oak, black	757	353	404
cherrybark	274	109	165
chestnut	—	—	—
laurel	1	—	1
northern red	455	221	234
post	1,236	801	435
scarlet	2	2	—
Shumard	39	15	24
southern red	730	589	141
water	357	112	245
white	1,356	893	463
Sweetbay	23	1	22
Sweetgum	1,288	611	677
Tupelo, black	383	216	167
Yellow-poplar	3	1	2
Other hardwoods	2,059	286	1,773
Total hardwoods	11,174	4,926	6,248

Table 2-9.—*Volume of all hardwoods on pine sites and hardwood sites, Florida* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	Million cubic feet		
Ash, spp.	366	2	364
Elm, spp.	88	4	84
Hackberry, spp.	21	1	20
Hickory, spp.	124	37	87
Maple, red	374	23	351
Oak, black	([1])	([1])	([1])
cherrybark	2	—	2
chestnut	—	—	—
laurel	645	146	499
northern red	—	—	—
post	22	15	7
scarlet	—	—	—
Shumard	3	1	2
southern red	54	49	5
water	270	104	166
white	16	8	8
Sweetbay	467	60	407
Sweetgum	420	93	327
Tupelo, black	1,168	158	1,010
Yellow-poplar	35	14	21
Other hardwoods	1,386	363	1,023
Total hardwoods	5,461	1,078	4,383

[1] Negligible

TABLE 2-10.—*Volume of all hardwoods on pine sites and hardwood sites, Georgia* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	Million cubic feet		
Ash, spp.	293	45	248
Elm, spp.	214	80	134
Hackberry, spp.	57	2	55
Hickory, spp.	761	501	260
Maple, red	768	244	524
Oak, black	283	188	95
cherrybark	23	12	11
chestnut	452	224	228
laurel	779	254	525
northern red	282	148	134
post	279	252	27
scarlet	335	247	88
Shumard	28	12	16
southern red	465	418	47
water	749	459	290
white	777	573	204
Sweetbay	251	37	214
Sweetgum	1,819	1,055	764
Tupelo, black	1,937	575	1,362
Yellow-poplar	982	616	366
Other hardwoods	1,465	658	807
Total hardwoods	12,999	6,600	6,399

TABLE 2-11.—*Volume of all hardwoods on pine sites and hardwood sites, Louisiana* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	----------*Million cubic feet*----------		
Ash, spp.	527	42	485
Elm, spp.	359	47	312
Hackberry, spp.	341	3	338
Hickory, spp.	676	197	479
Maple, red	271	51	220
Oak, black	20	19	1
cherrybark	208	110	98
chestnut	—	—	—
laurel	120	42	78
northern red	—	—	—
post	328	307	21
scarlet	—	—	—
Shumard	9	3	6
southern red	458	446	12
water	710	254	456
white	322	283	39
Sweetbay	72	36	36
Sweetgum	1,640	690	950
Tupelo, black	395	154	241
Yellow-poplar	31	10	21
Other hardwoods	3,392	391	3,001
Total hardwoods	9,879	3,085	6,794

TABLE 2-12.—*Volume of all hardwoods on pine sites and hardwood sites, Mississippi* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	Million cubic feet		
Ash, spp.	205	29	176
Elm, spp.	318	82	236
Hackberry, spp.	170	4	166
Hickory, spp.	698	356	342
Maple, red	137	53	84
Oak, black	119	94	25
cherrybark	236	120	116
chestnut	5	3	2
laurel	41	12	29
northern red	10	6	4
post	489	453	36
scarlet	43	39	4
Shumard	73	46	27
southern red	634	568	66
water	604	217	387
white	548	438	110
Sweetbay	212	63	149
Sweetgum	1,166	531	635
Tupelo, black	540	233	307
Yellow-poplar	268	122	146
Other hardwoods	1,900	358	1,542
Total hardwoods	8,416	3,827	4,589

TABLE 2-13.—*Volume of all hardwoods on pine sites and hardwood sites, North Carolina* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	Million cubic feet		
Ash, spp.	405	42	363
Elm, spp.	221	63	158
Hackberry, spp.	29	6	23
Hickory, spp.	912	422	490
Maple, red	1,639	502	1,137
Oak, black	453	219	234
cherrybark	64	40	24
chestnut	957	300	657
laurel	—	—	—
northern red	697	150	547
post	369	261	108
scarlet	760	420	340
Shumard	—	—	—
southern red	405	357	48
water	524	293	231
white	1,553	1,022	531
Sweetbay	58	7	51
Sweetgum	1,673	804	869
Tupelo, black	1,956[1]	298	1,658
Yellow-poplar	2,064	946	1,118
Other hardwoods	2,335	686	1,649
Total hardwoods	17,074	6,838	10,236

[1] Includes water tupelo.

TABLE 2-14.—*Volume of all hardwoods on pine sites and hardwood sites, Oklahoma* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	Million cubic feet		
Ash, spp.	54	5	49
Elm, spp.	116	18	98
Hackberry, spp.	24	1	23
Hickory, spp.	209	88	121
Maple, red	7	2	5
Oak, black	147	53	94
cherrybark	2	1	1
chestnut	—	—	—
laurel	—	—	—
northern red	25	12	13
post	407	226	181
scarlet	—	—	—
Shumard	25	4	21
southern red	88	35	53
water	34	6	28
white	94	62	32
Sweetbay	—	—	—
Sweetgum	56	32	24
Tupelo, black	32	18	14
Yellow-poplar	—	—	—
Other hardwoods	281	70	211
Total hardwoods	1,601	633	968

TABLE 2-15.—*Volume of all hardwoods on pine sites and hardwood sites, South Carolina* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	----------*Million cubic feet*----------		
Ash, spp.	308	42	266
Elm, spp.	204	71	133
Hackberry, spp.	67	9	58
Hickory, spp.	341	185	156
Maple, red	591	153	438
Oak, black	91	78	13
cherrybark	75	52	23
chestnut	58	35	23
laurel	499	113	386
northern red	68	55	13
post	149	132	17
scarlet	111	94	17
Shumard	11	6	5
southern red	194	170	24
water	469	268	201
white	382	287	95
Sweetbay	14	2	12
Sweetgum	1,373	636	737
Tupelo, black	1,318	296	1,022
Yellow-poplar	381	210	171
Other hardwoods	1,389	464	925
Total hardwoods	8,093	3,358	4,735

TABLE 2-16.—*Volume of all hardwoods on pine sites and hardwood sites, Tennessee* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	----------*Million cubic feet*----------		
Ash, spp.	302	42	260
Elm, spp.	243	26	217
Hackberry, spp.	97	4	93
Hickory, spp.	1,334	492	842
Maple, red	344	147	197
Oak, black	684	333	351
cherrybark	115	6	109
chestnut	1,057	571	486
laurel	—	—	—
northern red	494	208	286
post	343	139	204
scarlet	538	321	217
Shumard	11	2	9
southern red	339	132	207
water	45	1	44
white	1,348	530	818
Sweetbay	—	—	—
Sweetgum	366	53	313
Tupelo, black	252	111	141
Yellow-poplar	775	278	497
Other hardwoods	1,568	328	1,240
Total hardwoods	10,255	3,724	6,531

TABLE 2-17.—*Volume of all hardwoods on pine sites and hardwood sites, Texas* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	----------	*Million cubic feet*	----------
Ash, spp.	106	33	73
Elm, spp.	183	64	119
Hackberry, spp.	73	13	60
Hickory, spp.	253	155	98
Maple, red	51	25	26
Oak, black	28	20	8
cherrybark	133	69	64
chestnut	—	—	—
laurel	26	18	8
northern red	—	—	—
post	508	405	103
scarlet	—	—	—
Shumard	14	6	8
southern red	388	343	45
water	405	219	186
white	202	180	22
Sweetbay	34	10	24
Sweetgum	791	554	237
Tupelo, black	216	124	92
Yellow-poplar	—	—	—
Other hardwoods	811	355	456
Total hardwoods	4,222	2,593	1,629

TABLE 2-18.—*Volume of all hardwoods on pine sites and hardwood sites, Virginia* (Christopher et al. 1976)

Species	All sites	Pine sites	Hardwood sites
	Million cubic feet		
Ash, spp.	224	56	168
Elm, spp.	121	43	78
Hackberry, spp.	9	1	8
Hickory, spp.	1,034	372	662
Maple, red	921	384	537
Oak, black	644	337	307
cherrybark	31	17	14
chestnut	1,792	685	1,107
laurel	12	3	9
northern red	898	264	634
post	100	72	28
scarlet	897	510	387
Shumard	1	—	1
southern red	339	285	54
water	31	20	11
white	2,001	1,149	852
Sweetbay	4	2	2
Sweetgum	736	499	237
Tupelo, black	479	204	275
Yellow-poplar	1,360	805	555
Other hardwoods	2,017	410	1,607
Total hardwoods	13,651	6,118	7,533

The concentration of these hardwoods Southwide and on southern pine sites is shown in the maps of chapter 3 (figs. 3-1 through 3-32).

The foregoing summarizes hardwood survey data specific to southern pine sites. Additional state and regional data are periodically available, however, on the hardwood resource on all classes of sites.

Readers interested in the most current survey data should direct their queries to the Southern and Southeastern Forest Experiment Stations of the Forest Service. A sampling of recent references containing data on the 12-State region follows.

State and reference	Title
Alabama	
Beltz (1975a)	Alabama's timber resources updated, 1975
Hedlund and Earles (1973)	Forest statistics for Alabama counties
Murphy (1973)	Alabama forests: trends and prospects
Arkansas	
Beltz (1975b)	Arkansas's timber resources updated, 1975
Staff, Renewable Resources Evaluation Research Work Unit (1980)	Forest statistics for Arkansas counties
Van Sickle (1970)	Arkansas forest resource patterns

Georgia	
Morris and Steinbeck (1974)	Georgia's timber resource
Florida	
Knight and McClure (1971)	Florida's timber, 1970
Louisiana	
Bertelson (1974)	Louisiana forest industries, 1973
Earles (1975)	Forest statistics for Louisiana parishes
Maddocks (1976)	Hardwoods & wildlife—here today, here tomorrow. Part I: manage the hardwoods. Part II: pine trees for wildlife.
Murphy (1975)	Louisiana forests: status & outlook
Mississippi	
Beltz and Christopher (1970)	Computer program for updating timber resource statistics by county, with tables for Mississippi
Hedlund and Earles (1969)	Forest statistics for Mississippi counties
Van Sickle and Van Hooser (1969)	Forest resources of Mississippi
North Carolina	
Cost (1975)	Forest statistics for the Mountain Region of North Carolina, 1974
Knight (1975a)	A preview of "North Carolina's timber, 1974"
Knight (1975b)	North Carolina's timberland acreage is declining
Knight and McClure (1966)	North Carolina's timber
South Carolina	
Knight and McClure (1969)	South Carolina's timber, 1968
Oklahoma	
Murphy (1977)	East Oklahoma forests: trends and outlook
Earles (1976a)	Forest statistics for east Oklahoma counties
Tennessee	
Hedlund and Earles (1971)	Forest statistics for Tennessee
Murphy (1972)	Forest resources of Tennessee
Texas	
Bertelson (1975a)	East Texas forest industries, 1974
Earles (1976b)	Forest statistics for east Texas piney woods counties
Murphy (1976)	East Texas forests: status and trends
Virginia	
Knight and McClure (1967)	Virginia's timber, 1966

Some readers are likely to be interested in the timber resources of the border state of Missouri, for which references are available, as follows:

Reference	Title
Essex and Spencer (1974)	Timber resources of Missouri's eastern Ozarks—'72
Hahn and Vasilevsky (1975)	Timber resources of Missouri's Prairie region
Ostrom (1974)	Timber volume in Missouri counties

Southwide resource data have been reported in the following pubications:

Reference	Title
Bellamy (1972)	Southern pulpwood production, 1971
Bellamy (1974)	Southern pulpwood production, 1973
Beltz (1972)	Midsouth pulpwood movement
Beltz and Bertelson (1971)	Timber resource statistics for Midsouth counties, 1971
Bertelson (1973)	Southern pulpwood production, 1972
Bertelson (1975b)	Southern pulpwood production, 1974
Cruikshank and McCormack (1956)	The distribution and volume of hickory timber
Earles (1973)	Forest area statistics for Midsouth counties
Hair (1966)	Projected demands for hardwood veneer emphasize research-management needs
Harold (1976)	TVA is looking ahead at veneer timber opportunities
Hedlund and Knight(1969)	Hardwood distribution maps for the South
Hertzler (1951)	Southern hardwoods for veneer and plywood
Murphy[3]	The timber resource of the Midsouth
Ostermeier (1975)	The South's forest products industries: a major industrial sector
Quigley (1971)	The supply and demand situation for oak timber
Siegel (1963)	The changing hardwood lumber industry
Sternitzke (1973)	The South's timber resources: status and trends
Sternitzke (1974)	Eastern hardwood resources: trends and prospects
Sternitzke (1975)	Shifting hardwood trends in the South
Sternitzke (1976)	Impact of changing land use on delta hardwood forests

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[3] Murphy, P.A. The timber resource of the Midsouth. Paper presented at the Mid-South Section meeting to the For. Prod. Res. Soc. at Jackson, Miss., Oct. 13-14, 1976. 23p.

2-7 HARDWOOD BIOMASS ANALYSIS

Succeeding generations of wood technologists will probably continue current efforts to develop economic processes to convert ever smaller trees into useful commodities. These efforts may, in time, result in retrieval of most of the total biomass of each tree harvested.

The inventory data presented in figures 2-1 and 2-2 include stem and bark and are for trees 5 inches and larger in dbh outside bark to a 4-inch top measured outside bark. The inventory information in section 2-6 is confined to stem portions within these diameter limits but includes no bark. These diameter limits are based on past industrial practice. For example, a 1972 study in Alabama (Beltz and Chappell 1973) showed that loggers removed from the woods a volume about equal to volume estimated for these stands by Forest Survey standards.

These survey standards are closely related to currently merchantable volumes but substantially underestimate the total volume by omitting two major components:

- In trees 5 inches dbh and larger: roots, stumps, stembark, branches, tops, and foliage.
- In trees and shrubs smaller than 5 inches dbh: entire biomass above and below ground.

Young[4] estimated that these components of a forest of 63,000 acres in Maine are approximately equal in dry tonnage to that contained in the conventionally merchantable stem portions from trees 5 inches and larger in dbh.

For hardwoods on pine sites, the total unmerchantable biomass of complete trees in aggregate probably exceeds the biomass of merchantable portions as defined by current standards. For example, merchantable bole wood in 26 black oak trees ranging from 11.5 to 34.8 inches dbh amounted to only 39 percent of above- and below-ground dry biomass (Tennessee Valley Authority 1972); thus these trees contained 156 pounds (dry) of root, stump, bark, tops, branches, and foliage for every 100 pounds of dry merchantable stem.

While these proportions may vary for other species, it is likely that nearly 50 percent of the total biomass of pine-site hardwoods 5 inches dbh and larger is in portions usually considered unmerchantable. To this non-inventoried biomass should be added the biomass of trees less than 5 inches dbh. Average stem cubic volume for such trees is about 1 cubic foot, of which about one-fifth is bark; this stem volume comprises approximately three-fourths of the total-tree volume above ground (Phillips and McClure 1976). Such small hardwoods grow in profusion on most pine sites. It is probable, therefore, that on pine sites South-wide, the sum of these two non-inventoried hardwood components not only equals—but exceeds—the inventory described in section 2-6.

This conclusion is supported by reviews of the world literature. Keays and Hatton (1975) note that unmerchantable above-ground biomass of average hardwood stands is about equal in tonnage to the merchantable biomass. To this must be added the unused biomass of central stump-root systems of hardwoods growing on pine sites, amounting to about one-fifth the dry weight of the bark-free merchantable stem. Thus, even where hardwoods on pine sites are commercially harvested, rather than windrowed and burned, present practice leaves about 120 pounds of hardwood biomass on the site for every 100 pounds removed as merchantable.

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[4] Young, H. 1976. Tonnage of non-merchantable biomass on 63,000 acres of Maine woodlands is approximately equal to merchantable tonnage. Private communication to P. Koch dated August 23, 1976. 3p.

A major objective of this text is to characterize the non-inventoried, as well as the inventoried, portions of hardwoods on pine sites and to describe processing systems for their utilization. In view of this, section 16-1 contains analyses—by species—of complete-tree and whole-tree biomass. See also table 27-97 and the tabulation immediately following Equation 27-23 in the opening pages of Chapter 27.

LITTER

Litter under hardwoods, i.e., the uppermost layer of organic debris on the forest floor composed of leaves, bark fragments, twigs, and fruit, is yet another major part of the forest biomass. Such litter is frequently incinerated during controlled burns. Its retrieval for utilization is not recommended because of harmful effects on long-term site productivity, but it is useful to know something about litter tonnages.

Blow (1955) found that the quantity of litter in several upland oak stands in eastern Tennessee ranged from 2 to 12 tons per acre (at field moisture content), depending on past fire, cutting practices, and stand composition. Annual leaf fall from one mixed oak stand added an average of 1.3 tons of litter per acre (ovendry basis) to the forest floor. Total accumulated litter peaked at 5.4 tons in December following leaf fall, decreasing to a fairly stable low weight of 4.2 tons in August (ovendry basis).

The moisture content of hardwood litter, at field capacity, averaged 135 percent of its ovendry weight. Temporary retention immediately after a rain increased moisture to 175 percent. Moisture content of litter completely saturated in the laboratory reached 250 percent. Normal moisture content of litter varies with time since the last rain of 0.25 inch or more. Moisture decreases rapidly to 41 percent in 10 days and then gradually to 25 percent at 20 days. Here, it becomes relatively stable, subject to minor fluctuations due to relative humidity.

Forest floor fuelbeds under 20- and 40-year-old black oak stands in southeast Missouri averaged 6.4 and 8.3 tons per acre and 4.0 and 4.2 inches in depth, respectively. Loose litter averaged 2.0 and 2.9 tons per acre and 3.3 inches in depth. Bulk density of litter averaged 0.33 and 0.49 lb/ft^3 and of total forest floor 0.89 and 1.10 lbs/ft^3, respectively. The foregoing weights (ovendry basis) were observed by Crosby and Loomis (1974).

Under a pine-oak type forest in the southern Appalachians (Bent Creek Experimental Forest), accumulated litter on one site after at least 10 years without disturbance amounted to 7,900 pounds per acre (ovendry basis); standard deviation was 1,500 pounds per acre (Sims 1932). On another site in the same forest, the average was 6,300 pounds with standard deviation of 800 pounds. Annual leaf fall was 3,100 pounds per acre (ovendry basis) on one series of sites and 2,600 pounds per acre on a second series. In this experiment, it appeared that normal accumulation of litter in all stages of decomposition weighed two or three times as much as that deposited in one year. Sims (1932) concluded that, inasmuch as decomposition is progressive and probably begins the first summer after deposition, more than 3 years are required for the disappearance of any 1 year's litter.

In Union County, South Carolina, Metz (1952) observed that, in three stands of mixed hardwoods and shortleaf pine, annual leaf and needle fall was 3,472 pounds per acre with accumulated litter totalling 4,762 pounds per acre (ovendry basis). Under pure hardwoods, leaf fall was 3,818 pounds per acre annually with accumulated litter averaging 4,502 pounds per acre (ovendry basis).

The forest floor under low-grade oak stands (438 trees per acre averaging 5.4 inches in diameter) sampled near Oxford, Mississippi, averaged about 0.4 inch thick and totalled slightly over 5 tons per acre (ovendry basis); deadening of the hardwoods quickly caused a breakdown of the forest floor, and litter would have been completely gone in 6 years had not other vegetation invaded the area (Dickerson 1972).

It is evident that the 138-million-acre southern pinery carries an enormous tonnage of litter on the forest floor; the annual leaf and needle fall on these acres probably approaches the weight of the inventoried net annual growth of both pine and hardwood.

2-8 BIOLOGICAL POTENTIAL

Hardwood growth in the South varies significantly by site, stocking, and species. The Southwide average is low, however; based on inventories of stems 5 inches in dbh and larger, hardwood growth is only 16.7 cubic feet per acre per year, i.e., 0.27 ton ovendry per acre (U.S. Department of Agriculture, Forest Service 1974, p. 62). On southern pine sites, hardwood growth would probably be slower. Inclusion of stems smaller than 5 inches would increase tonnages somewhat.

While site-related data are meager, well-stocked stands of hardwood on pine sites probably grow only a third to a half the annual volume produced by the same sites when stocked with southern pine. For example (see tables 27-9 and 27-45), 30-year-old second-growth upland oak on site index 60 (50-year-height, feet) with 84 square feet of **basal area** per acre, yielded 10.35 cords of merchantable stem per acre to a 4-inch top outside bark; this amounts to 0.34 cord (29 cubic feet of wood) per year (Schnur 1937, p. 8). (Basal area is defined as the summation of cross-sectional areas of stumps if trees are cut 4½ feet from the ground.)

Dale (1972) found that upland oak stands on poor sites in Iowa, Missouri, Illinois, Indiana, Ohio, and Kentucky produced about one-half cord per acre per year from age 20 to 30, and somewhat more in the 10 years from age 30 to 40; growth would be considerably less from age 1 to 20 years.

On other studies in the Central States, Gingrich (1971) found that upland hardwood stands at age 50 yielded 0.4 to 0.9 cord per acre per year depending on site and thinning regime, as follows (see table 27-11 for data on unthinned plots):

Site index (feet)	Unthinned	First thinned at age 10
	Cords yield per acre per year	
55	0.39	0.61
65	.54	.72
75	.60	.92

In the South, Smith et al. (1975) found that fully stocked, even-aged, mixed-species hardwood stands on upland slopes and ridge sites produced about 40 cubic feet of stemwood per acre per year to age 40 (table 27-44); their data were based on sample plots extending from Virginia to Florida and west to Louisiana and Arkansas. On southern upland slopes and ridges Porterfield (1972) found that growth of hardwoods averaged about one-half a cord per acre per year (table 27-12).

A study of unmanaged upland hardwoods in north Mississippi showed much lower periodic growth rates—only 10 cubic feet per acre per year (Williston 1969).

These data represent only a few circumstances, but illustrate that hardwood stands on pine sites probably yield less than half a cord per acre per year. The literature review by Evans et al. (1975) provides a broader range of data on growth and yield of hardwoods in the South and East (see table 27-10).

Pine grows much more rapidly. For example, on an average southern pine site, 30-year old loblolly pine (*P. taeda* L.) should yield 31 cords of peeled wood to a 4-inch top; this amounts to about one cord per acre per year of peeled wood or about 95 cubic feet of wood per year (U.S. Department of Agriculture, Forest Service 1976, p. 68).

Boyce et al. (1975a) estimate that the biological potential of the loblolly pine ecosystem east of the Mississippi River ranges from 95 to 129 cubic feet per acre per year, and averages about 101 cubic feet. For the slash pine (*P. elliottii* Engelm. var. *elliottii*) ecosystem east of the Mississippi River, the biological potential has been estimated at about 85 cubic feet per acre per year (Boyce et al. 1975b, p. 16).

The rapid growth of southern pine compared to hardwood growth on the same sites presents a major opportunity for increased production of wood from southern forests; this opportunity is the major impetus for converting such hardwood stands to pine. The economics of such type conversion is analyzed in Anderson and Guttenberg (1974). Needed hardwoods can be grown more efficiently in coves and bottoms more suited to their requirements.

A different approach has been suggested for some southern pine sites—intensive **coppice** management of certain hardwood species. In this approach, intensively cultivated hardwoods would be grown from cuttings and sprouts through short rotations on close spacing to provide wood for fiber or energy. With fertilization and irrigation of every acre as required, yields of 5 to 12 tons of dry biomass per acre per year have been suggested as achievable over a broad range of sites throughout the South. Such proposals have met with considerable skepticism on the part of many foresters and wood technologists. Others, principally engineers and agronomists, think these yields may be achievable. A major study of the subject is underway by METREK, Division of MITRE Corporation, McLean, Va., in cooperation with Georgia Pacific Corporation, Portland, Ore.[5] While this study is not complete, the analysis to date is both interesting and challenging. Time will tell if the agronomists are correct in their predictions of dry biomass production of 5 to 12 tons per acre over a broad range of intensively cultivated southern sites.

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[5] Energy Research and Development Administration, Division of Solar Energy, Fuels from Biomass Systems Branch. A conference—silviculture biomass plantations. February 15-16, 1977, Reston, Va.

To conclude these comments on biomass and biological potential, inventoried hardwood production on pine sites (fig. 2-1) is but one-third the total hardwood biomass grown on these sites; another third is in roots, stumps, tops, and branches of inventoried stems and in trees smaller than 5 inches dbh; still another third is in annual leaf fall. Finally, in the opinion of some knowledgeable agronomists, there is potential for a several-fold increase, over 1970, in biomass production throughout a broad range of southern pine sites—but new silvicultural methods would be required.

2-9 OWNERSHIP PATTERNS

Some understanding of ownership patterns in southern commercial forest land is central to any plan for utilization. No data specific to southern pine sites are at hand, but the outlook study (U.S. Department of Agriculture, Forest Service 1974, p. 54) provides information on southern commercial forest land in general; probably ownership patterns on pine sites are similar. Percentages of acreage, by owner class, are as follows:

Owner class	1952	1970	Projection to 2000
	Percent		
National Forest	5	6	6
Other public	3	3	3
Forest industry	17	18	20
Farm and miscellaneous private	75	73	71
Total	100	100	100

An approximation of ownerships of southern pine sites can also be derived from *Forest Statistics for the United States, by State and Region, 1970* (U.S. Department of Agriculture Forest Service 1972, p. 91-92); grouping of pine ownerships with oak/pine and oak/hickory ownerships gives data as follows: National Forest, 6.5%; other public, 3%; forest industry, 18.5%, and farm and miscellaneous private, 72%.

In 1970, harvests of hardwood roundwood by ownership class were as follows:

Ownership class	Fraction of total hardwood volume harvested
	Percent
National Forest	1
Other public	3
Forest industry	20
Farm and miscellaneous private	76
Total	100

While the foregoing proportions reflect hardwoods produced on both hardwood and pine sites, distribution of harvests from pine sites should be quite similar. It is evident that farms and miscellaneous private lands comprise the major forest acreage and supply a correspondingly large share of the hardwood harvested in the South (U.S. Department of Agriculture, Forest Service 1974, p. 54 and 59).

2-10 LITERATURE CITED

Anderson, W.C. and S. Guttenberg 1971. Investor's guide to converting southern oak-pine types. U.S. Dep. Agric. For. Serv., Res. Pap. SO-72. 10 p.

Bellamy, T.R. 1972. Southern pulpwood production, 1971. U.S. Dep. Agric. For. Serv., Resour. Bull. SE-23. 20 p.

Bellamy, T.R. 1974. Southern pulpwood production, 1973. U.S. Dep. Agric. For. Serv., Resour. Bull. SE-29. 21 p.

Beltz, R.C. 1972. Midsouth pulpwood movement. Pulpwood Prod. 20(4):14, 16.

Beltz, R.C. 1975a. Alabama's timber resources updated, 1975. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-55. 10 p.

Beltz, R.C. 1975b. Arkansas' timber resources updated, 1975. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-56. 10 p.

Beltz, R.C. and D. F. Bertelson 1971. Timber resource statistics for Midsouth counties, 1971. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-31. 26 p.

Beltz, R.C. and T. W. Chappell 1973. Trends in product logging and tree utilization in Alabama. For. Prod. J. 23(8):15-16.

Beltz, R.C. and J. F. Christopher 1970. Computer program for updating timber resource statistics by county, with tables for Mississippi. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-23. 22p.

Bertelson, D.F. 1973. Southern pulpwood production, 1972. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-41. 25p.

Bertelson, D.F. 1974. Louisiana forest industries, 1973. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-51. 20 p.

Bertelson, D.F. 1975a. East Texas forest industries, 1974. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-57. 20 p.

Bertelson, D.F. 1975b. Southern pulpwood production, 1974. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-54. 24 p.

Billings, W.D. 1938. The structure and development of old field shortleaf pine stands and certain associated physical properties of the soil. Ecol. Monogr. 8(3):437-499.

Blow, F.E. 1955. Quantity and hydrologic characteristics of litter under upland oak forests in eastern Tennessee. J. of For. 53:190-195.

Bormann, F.H. 1953. Factors determining the role of loblolly pine and sweetgum in early old-field succession in the Piedmont of North Carolina. Ecol. Monogr. 23(4):339-358.

Boyce, S.G., J.P. McClure, and H. S. Sternitzke 1975a. Biological potential for the loblolly pine ecosystem east of the Mississippi River. U.S. Dep. Agric. For. Serv., Res. Pap. SE-142. 27 p.

Boyce, S.G., J.P. McClure, and H. S. Sternitzke 1975b. Biological potential for the slash pine ecosystem. U.S. Dep. Agric. For. Serv., Res. Pap. SE-141. 29 p.

Boyd, C.W., P. Koch, H.B. McKean, C.R. Morschauser, S.B. Preston, and F.F. Wangaard 1976. Wood for structural and architectural purposes. Wood and Fiber 8:3-72.

Boyd, C.W., P. Koch, H.B. McKean, C. R. Morschauser, S.B. Preston, and F.F. Wangaard 1977. Highlights from wood for structural and architectural purposes. For. Prod. J. 27(2):10-20.

Christopher, J.F., H.S. Sternitzke, R.C. Beltz, J.M. Earles, and M.S. Hedlund 1976. Hardwood distribution on pine sites in the South. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-59. 27 p.

Cost, N.D. 1975. Forest statistics for the Mountain Region of North Carolina, 1974. U.S. Dep. Agric. For. Serv., Resour. Bull. SE-31. 33p.

Croker, T.C., Jr. 1969. Ecology of an ideal forest community in the longleaf-slash pine region. *In* The ecology of southern forests, pp. 73-90. La. State Univ. 17th annu. for. symp. proc. 1968. Baton Rouge, La.: La. State Univ. Press.

Crosby, J.S. and R.M. Loomis 1974. Some forest floor fuelbed characteristics of black oak stands in southeast Missouri. U.S. Dep. Agric. For. Serv., Res. Note NC-162. 4 p.

Cruikshank, J.W. and J.F. McCormack 1956. The distribution and volume of hickory timber. U.S. Dep. Agric. For. Serv., Hickory Task Force Rep. No. 5. 12 p., Southeast. For. Exp. Stn., Asheville, N.C.

Dale, M.E. 1972. Growth and yield predictions for upland oak stands 10 years after initial thinning. U. S. Dep. Agric. For. Serv., Res. Pap. NE-241. 21 p.

Dickerson, B.P. 1972. Changes in the forest floor under upland oak stands and managed loblolly pine plantations. J. of For. 70:560-562.

Earles, J.M. 1973. Forest area statistics for Midsouth counties. U. S. Dep. Agric. For. Serv., Resourc. Bull. SO-40. 64 p.

Earles, J.M. 1975. Forest statistics for Louisiana parishes. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-52. 85 p.

Earles, J.M. 1976a. Forest statistics for east Oklahoma counties. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-62. 40 p.

Earles, J.M. 1976b. Forest statistics for east Texas pinewoods counties. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-60. 40 p.

Essex, B.L. and J. S. Spencer, Jr. 1974. Timber resource of Missouri's eastern Ozarks—'72. U.S. Dep. Agric. For. Serv., Resour. Bull. NC-19. 62 p.

Evans, T.F., H.E. Burkhart, and R.C. Parker 1975. Site and yield information applicable to Virginia's hardwoods: a review. M.F. thesis. Va. Polytech. Inst. and State Univ., Blacksburg, Va. 143 p.

Fitzgerald, C.H., F.A. Peevy, and D.E. Fender 1973. Rehabilitation of forest land: the southern region. J. of For. 71:148-152.

Gingrich, S.F. 1971. Management of young intermediate stands of upland hardwoods. U.S. Dep. Agric. For. Serv., Res. Pap. NE-195. 26 p.

Hahn, J.T. and A. Vasilevsky 1975. Timber resource of Missouri's Prairie Region. U.S. Dep. Agric. For. Serv., Resour. Bull. NC-26. 100 p.

Hair, D. 1966. Projected demands for hardwood veneer emphasize research-management needs. For. Prod. J. 16(1):28-30.

Harold, M.R. 1976. TVA is looking ahead at veneer timber opportunities. South Lumberman 233(2895):74-77.

Hedlund, A. and J.M. Earles 1969. Forest statistics for Mississippi counties. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-15. 24 p.

Hedlund, A. and J.M. Earles 1971. Forest statistics for Tennessee counties. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-32. 58 p.

Hedlund, A. and J.M. Earles 1973. Forest statistics for Alabama counties. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-39. 65 p.

Hertzler, R.A. 1951. Southern hardwoods for veneer and plywood. South. Lumberman 182(2279):44-50.

Hough, W.A. 1972-73. Prescribed burning in the South surveyed, analyzed. Fire Control Notes 34(1):4-5.

Howe, J.P. and P. Koch 1976. Dowel-laminated crossties—performance in service, technology of fabrication, and future promise. For. Prod. J. 26(5): 23-30.

Hse, C.-Y. P. Koch, C.W. McMillan, and E. W. Price 1975. Laboratory-scale development of a structural exterior flakeboard from hardwoods growing on southern pine sites. For. Prod. J. 25(4):42-50.

Josephson, H.R. 1974. Hardwood resources—have we enough in the right places? Tappi 57(10):105-107.

Keays, J.L. 1971. Complete tree utilization—an analysis of the literature. Part I: unmerchantable top of bole. Can. For. Serv. Rep. VP-X-69, 98 p. West. For. Prod. Lab., Vancouver, B.C., Can.

Keays, J.L. and J.V. Hatton 1975. The implication of full-forest utilization on worldwide supplies of wood by year 2000. Pulp & Pap. Int. 17(6):49-52.

Knight, H.A. 1975a. A preview of "North Carolina's timber, 1974." U.S. Dep. Agric. For. Serv., Resour. Note SE-224. 4 p.

Knight, H.A. 1975b. North Carolina's timberland acreage is declining. U.S. Dep. Agric. For. Serv., Res. Note SE-231. 5 p.

Knight, H.A. and J.P. McClure 1966. North Carolina's timber. U.S. Dep. Agric. For. Serv., Resour. Bull. SE-5. 47 p.

Knight, H.A. and J.P. McClure 1967. Virginia's timber, 1966. U.S. Dep. Agric. For. Serv., Resour. Bull. SE-8. 47 p.

Knight, H.A. and J.P. McClure 1969. South Carolina's timber, 1968. U.S. Dep. Agric. For. Serv., Resour. Bull. SE-13. 44 p.

Knight, H.A. and J.P. McClure 1971. Florida's timber, 1970. U.S. Dep. Agric. For. Serv., Resour. Bull. SE-20. 48 p.

Koch, P. 1973. Structural lumber laminated from ¼-inch rotary-peeled southern pine veneer. For. Prod. J. 23(7):17-25.

Maddocks, J. 1976. Hardwoods & wildlife—here today, here tomorrow. Part I: manage the hardwoods. Part II: pine trees for wildlife. For. & People 26(2):10-13, 32-36; 14-16, 44-45.

Metz, L.J. 1952. Calcium content of hardwood litter four times that from pine; nitrogen double. U.S. Dep. Agric. For. Serv., Res. Note No. 14. 2 p.

Mirov, N.T. 1967. The genus *Pinus*. 602 p. New York, N.Y.: The Ronald Press Co.

Morris, D.J. and K. Steinbeck 1974. Georgia's timber resource. Ga. For. Res. Pap. No. 77, 9 p.

Murphy, P.A. 1972. Forest resources of Tennessee. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-35. 33 p.

Murphy, P.A. 1973. Alabama forests: trends and prospects. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-42. 36 p.

Murphy, P.A. 1975. Louisiana forests: status & outlook. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-53. 31 p.

Murphy, P.A. 1976. East Texas forests: status and trends. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-61. 25 p.

Murphy, P.A. 1977. East Oklahoma forests. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-63. 20 p.

Murphy, P.A. and H.A. Knight 1974. Hardwood resources on southern pine sites. For. Prod. J. 24(7):13-16.

Oosting, H.J. 1942. An ecological analysis of the plant communities of Piedmont, North Carolina. The Am. Midland Nat. 28(1):1-126.

Ostermeier, D. 1975. The South's forest products industries: a major industrial sector. South. Lumberman 231(2872):83-84

Ostrom, A.J. 1974. Timber volume in Missouri counties. U.S. Dep. Agric. For. Serv., Res. Note NC-179. 4 p.

Phillips, D.R. and J.P. McClure 1976. Composition, volume, and physical properties of the hardwood understory. Proc. fourth annu. hardwood symp. Hardwood Res. Counc., p. 22-29.

Quarterman, E. and C. Keever 1962. Southern mixed hardwood forest: climax in the southeastern Coastal Plain, U.S.A. Ecol. Monogr. 32(2):167-185.

Quigley, K.L. 1971. The supply and demand situation for oak timber. *In* Oak symp. proc., pp. 30-36. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn, Upper Darby, Pa.

Schnur, G.L. 1937. Yield, stand, and volume tables for evenaged upland oak forests. U.S. Dep. Agric. For. Serv., Tech. Bull. No. 560, 87 p. U.S. Govt. Print. Off., Washington, D.C.

Siegel, W.C. 1963. The changing southern hardwood lumber industry. South. Lumberman 207(2585):83-86.

Sims, I.H. 1932. Litter deposition and accumulation in the pine-oak type of the southern Appalachians. J. of For. 30:90-91.

Smith, H.D., W.L. Hafley, D.L. Holley, and R.C. Kellison 1975. Yields of mixed hardwood stands occurring naturally on a variety of sites in the southern United States. Sch. of For. Resourc., N.C. State Univ. Tech. Rep. No. 55, 32 p.

Staff, Renewable Resources Evaluation Research Work Unit 1980. Forest statistics for Arkansas counties. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-76. 77 p.

Sternitzke, H.S. 1973. The South's timber resources: status and trends. *In* The South's third forest-opportunities, action, responsibilities, pp. 5-11. La. State Univ. 22nd annu. for symp. proc.

Sternitzke, H.S. 1974. Eastern hardwood resources: trends and prospects. For. Prod. J. 24(3):13-16.

Sternitzke, H.S. 1975. Shifting hardwood trends in the South. South. Lumberman 231(2872):72-73, 42A.

Sternitzke, H.S. 1976. Impact of changing land use on delta hardwood forests. J. of For. 74:25-27.

Sternitzke, H.S. and T.C. Nelson 1970. The southern pines of the United States. Econ. Bot. 24(2):142-150.

Suchsland, O. and G.E. Woodson 1976. Properties of medium-density fiberboard produced in an oil-heated laboratory press. U.S. Dep. Agric. For. Serv., Res. Pap. SO-116. 10.

Tennessee Valley Authority 1972. Biomass estimates of black oak tree components. Tech. Note B1, 24 p. Norris, Tenn.: Tenn. Vall. Auth.

U.S. Department of Agriculture, Forest Service 1972. Forest Statistics for the United States, by State and Region, 1970. 96 p. Washington, D.C.: U.S. Govt. Print. Off.

U.S. Department of Agriculture, Forest Service 1974. The outlook for timber in the United States. U.S. Dep. Agric. For. Serv., Resour. Rep. No. 20, 374 p. U.S. Govt. Print. Off., Washington, D.C.

U.S. Department of Agriculture, Forest Service, 1976. Volume, Yield, and stand tables for second-growth southern pines. U.S. Dep. Agric. For. Serv., Misc. Publ. No. 50. 202 p. U.S. Govt. Print. Off., Washington, D.C.

Van Sickle, C.C. and D.D. Van Hooser 1969. Forest resources of Mississippi. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-17. 34 p.

Van Sickle, C.C. 1970. Arkansas forest resource patterns. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-24. 34 p.

Wakeley, P.C. 1969. Effects of evolution on southern pine wood. For. Prod. J. 19(2):16-20.

Williston, H.L. 1969. Unmanaged growth in north Mississippi uplands. U.S. Dep. Agric. For. Serv., Res. Note SO-90. 4 p.

3

Species

Major portions of data drawn from research by:

- C.A. Brown
- J.F. Christopher and his associates
- H.E. Grelen
- R. Hedlund
- H.A. Knight
- F.G. Manwiller
- U.S. Department of Agriculture, Forest Service

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CHAPTER 3

Species

3-1 DESCRIPTION AND RANGE

Growth characteristics, range, and volume of the species strongly influence utilization; brief descriptions therefore seem appropriate. Unless otherwise noted, the descriptions that follow are condensed from *Silvics of forest trees of the United States*, a work that should be consulted if fuller information is desired (U.S. Department of Agriculture, Forest Service 1965). Hardwood trees growing on southern pine sites generally are smaller and have poorer form than those growing on more favorable sites. Drawings of winter silhouettes presented in section 3-2, therefore, depict typical 6-inch trees on pine sites; such trees, all species considered, average close to 40 years of age (table 3-1). See tables 16-3 and 16-10 for additional data on dimensions and biomass distribution in these 6-inch trees. Stump-root biomass data are given in section 14-3, bark biomass in section 13-3, and foliage biomass in section 15-2. As noted in chapter 2, 46 percent of the inventoried hardwood volume on pine sites (5 inches dbh and larger) is in trees less than 11 inches in diameter.

Computer-plotted maps of relative concentrations of the species on pine sites are from Christopher et al. (1976). On these maps, the lightest shading indicates locations where volume of the species on pine sites is negligible; there may be, however, appreciable volume of the species at these locations on true hardwod sites.

For comparative purposes, some earlier maps prepared by Hedlund and Knight (1969) depict concentrations of 7 of the non-oaks plus certain of the white oaks and red oaks throughout the 12-State southern region, wherever they occur on both pine and hardwood sites. Readers desiring information on the North American extent of the species' botanical ranges, are referred to the maps contained in Little (1971).

Ranges of many of the species extend considerably north of the 12 Southern States; such species tolerate the frequent freezing temperatures and deep snows of the northern states. Climate in the 12 Southern States is milder, with snow rarely falling on the Coastal Plain, and infrequently in the Highlands (fig. 2-3). For 22 localities in the region (table 3-2), minimum recorded frost-free days in any year range from 260 in Asheville, North Carolina, to 363 in Orlando, Florida. Annual rainfall in the southern pine region of these states is generally 45 to 50 inches, but varies from less than 40 inches along the western edge of the region to perhaps 80 inches in the parts of the Appalachian Mountains. Rainfall is generally greatest adjacent to the Gulf Coast and least in the northwesterly part of the region (table 3-2).

The descriptions that follow are in alphabetical order by common names of the species.

TABLE 3-1.—*Age, height, weight, and 10-year diameter growth data for hardwood trees approximately 6 inches in dbh collected from southern pine sites throughout each species' southern range, in order of increasing range of diameter growth*[1]

Species	Dbh		Age		Height		Average 10-year diameter growth	Average tree weight (ovendry)[2]
	Range	Average	Range	Average	Range	Average		
	-----*Inches*-----		------*Years*------		-------*Feet*-------		*Inches*	*Pounds*
Tupelo, black	5.5-6.2	5.8	30-102	58.9	25-55	40.3	1.0	110
Hickory, spp	5.6-6.5	6.0	32-101	54.5	36-51	44.8	1.1	151
Oak, post	5.7-6.2	6.0	32-86	50.6	30-44	39.0	1.2	137
Elm, winged	5.5-6.5	6.0	33-68	48.7	34-57	45.4	1.2	142
Oak, white	5.6-6.2	5.9	31-62	41.5	40-55	47.4	1.4	144
Maple, red	5.5-6.1	5.8	29-60	40.4	40-58	49.6	1.4	142
Oak, northern red	5.5-6.4	5.9	22-60	40.4	39-63	52.4	1.5	180
Ash, white	5.5-6.5	5.9	26-71	40.1	43-64	49.7	1.5	138
Sweetbay	5.6-6.2	5.8	20-58	39.3	21-58	44.9	1.5	123
Elm, American	5.5-6.3	5.9	25-60	40.0	38-56	46.8	1.5	127
Oak, water	5.5-6.3	5.9	29-64	39.4	41-59	53.9	1.5	176
Oak, blackjack	5.6-6.4	6.0	20-52	39.0	25-47	33.1	1.5	125
Oak, black	5.5-6.5	6.0	24-58	38.8	35-64	48.6	1.5	170
Ash, green	5.6-6.4	5.9	27-52	36.7	27-63	47.4	1.6	151
Oak, southern red	5.8-6.5	6.0	21-50	34.9	30-58	43.3	1.7	140
Oak, Shumard	5.5-6.5	6.1	22-48	34.5	44-67	51.7	1.8	185
Oak, scarlet	5.6-6.4	5.8	16-40	32.6	37-58	46.2	1.8	156
Oak, laurel	5.6-6.4	6.0	18-42	32.6	43-56	47.8	1.8	170
Oak, cherrybark	5.6-6.3	6.0	20-46	32.3	34-59	47.3	1.9	152
Sweetgum	5.5-6.2	5.9	20-50	29.4	37-62	46.8	2.0	97
Hackberry	5.5-6.4	6.1	19-40	28.3	35-54	44.5	2.2	118
Yellow-poplar	5.8-6.4	6.1	8-58	27.1	42-59	53.5	2.3	123

[1] Data from Manwiller (1975) and from F.G. Manwiller's studies FS-SO-3201-1.38 and 1.39, Southern Forest Experiment Station, U.S. Forest Service. Each average value represents data from 10 trees.

[2] Includes wood and bark of the stem above a 6-inch-high stump and all branch portions with diameter outside bark of 0.5 inch or more.

ASH (*Fraxinus* spp.)

Only two species, white and green ash, of the sixteen ashes occurring in the Unites States are commercially important in the South for wood products (Stewart and Krajicek 1973). Two less common species, pumpkin ash (*F. profunda* (Bush) Bush) and blue ash (*F. quadrangulata Michx.*) are grouped with them for survey (fig. 3-1) and are sold in the trade as **white ash**.

TABLE 3-2.—*Temperatures, frost-free days, and annual precipitation in selected cities of 12 Southern States* (Data from U. S. Weather Bureau)

State and city	Temperatures			Frost-free days annually	Mean precipitation
	Mean annual	Record high	Record low		
	------------°F-----------			*Days*	*Inches*
Alabama					
Mobile	67.4	102	8	346-365	67.0
Birmingham	62.4	102	−4	305-363	53.2
Arkansas					
Hot Springs	63.3	111	−1	314-363	54.9
Fayetteville	58.5	111	−10	274-358	42.4
Florida					
Orlando	71.8	99	24	363-365	51.2
Tallahassee	67.7	100	10	330-365	61.6
Georgia					
Rome	60.4	106	−5	283-364	52.3
Savannah	66.4	100	9	319-365	48.9
Louisiana					
Baton Rouge	67.4	102	10	341-365	54.1
Shreveport	65.9	107	3	331-364	44.7
Mississippi					
Biloxi	68.1	104	9	352-365	59.6
Greenwood	64.0	105	−4	321-361	51.1
North Carolina					
Asheville	55.7	96	−7	260-359	45.2
Raleigh	59.1	98	0	284-361	42.5
Oklahoma					
Tulsa	59.7	110	−3	276-355	37.1
South Carolina					
Charleston	64.7	103	8	330-365	52.1
Greenville	60.6	99	−6	298-363	47.5
Tennessee					
Knoxville	59.7	99	−9	294-359	46.2
Memphis	61.6	106	−13	306-359	49.1
Texas					
Lufkin	66.9	108	−2	327-364	43.0
Virginia					
Richmond	58.1	104	−12	279-359	44.2
Roanoke	56.9	100	−1	268-353	41.2

Lumber of the four species is generally classified into two groups based on texture or hardness and weight. These are called **cabinet grade** and **tough texture** (or **firm and better**). The former is useful where strength is less important, the latter, for specialties demanding high strength (Southern Hardwood Lumber Manufacturers' Association (n.d.a, b)). *Fraxinus americana* L. will generally produce a greater proportion of tough-textured stock than the other ash species.

Some handle specifications calling for tough-texture wood require not less than 5 or more than 17 growth rings per inch for handles of the best grade; the addition of a weight requirement of 43 or more pounds per cubic foot at 12 percent moisture content will assure excellent material (U.S. Department of Agriculture, Forest Service 1974, p. 1-5).

Figure 3-1 shows the distribution of these ash species Southwide on all sites. Of the total volume of ash species in the South (tables 2-7 through 2-18), 13.2 percent is on pine sites. Concentrations of this pine-site volume of ash species (fig. 3-2) are greatest in Virginia (56 million cubic feet), Alabama (53), and Arkansas (50). Georgia has 45 million cubic feet on pine sites; Louisiana, North Carolina, South Carolina, and Tennessee all have 42, while Texas has 33 and Mississippi 29 million. Florida and Oklahoma have least (2 and 5 million cubic feet, respectively.)

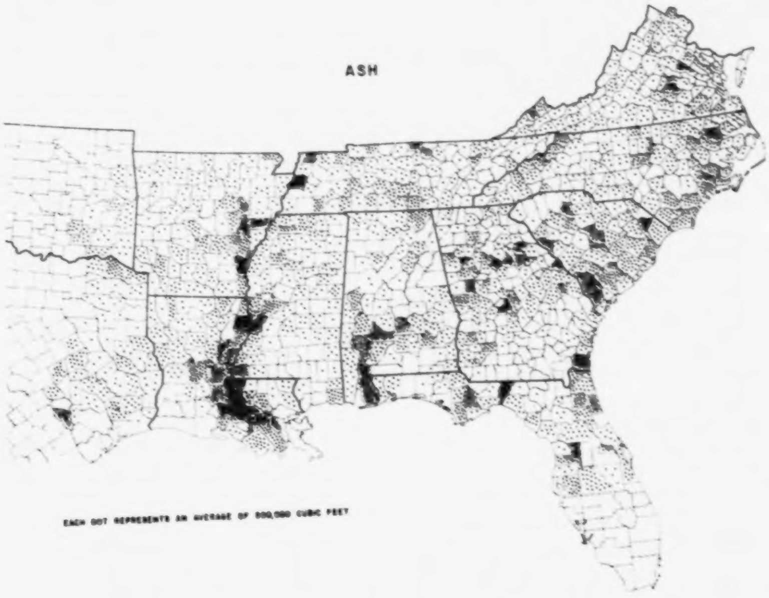

Figure 3-1.—Distribution and volume of ash (*Fraxinus* spp.) in the 12 Southern States (Drawing after Hedlund and Knight 1969.)

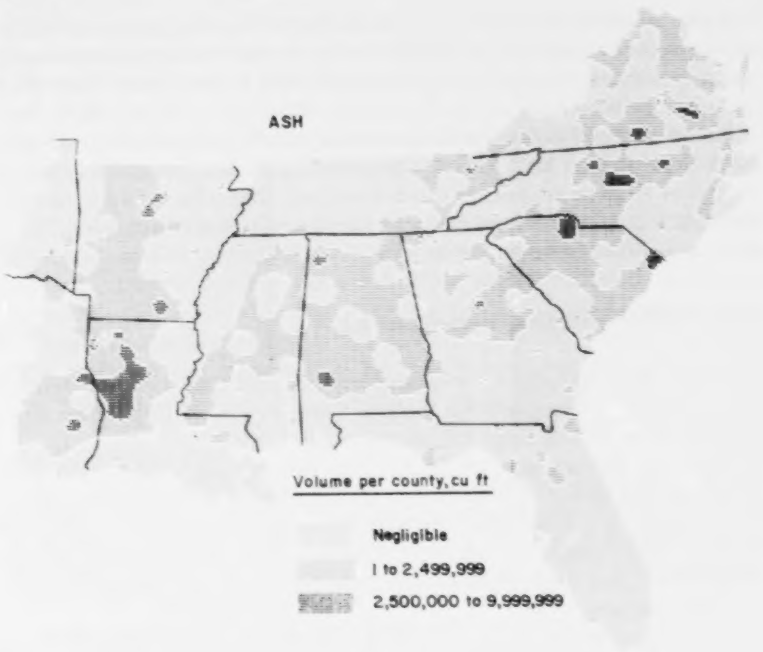

Figure 3-2.—SYMAP computer map of distribution and concentrations of ash (*Fraxinus* spp.) on pine sites (Drawing after Christopher et al. 1976.)

ASH, GREEN (*Fraxinus pennsylvanica* Marsh.)

Green ash, the most widely distributed of all American ashes, occurs throughout the South except peninsular Florida. Its range extends north into Canada. Natural stands of green ash are most common on alluvial soils, but this species also grows well on moist upland soils, and has proved useful for shelterbelts.

Flowers of green ash appear before leaf buds enlarge. Usually flowering commences when trees are 3 to 4 inches in diameter and 20 feet tall. A high percentage of favorably situated male and female trees of flowering size flower annually, and many female trees fruit annually.

Seed ripen in the fall and continue to fall until winter or early spring. Most of the seed is wind-dispersed within a few hundred feet of the parent trees. Freshly collected green ash seed is dormant because of an impermeable seed coat, but the dormancy can be overcome by moist stratification for 60 to 90 days at refrigerator temperatures.

Young vigorous, uninjured, open-grown trees grow a single, straight stem until 15 or more feet tall. Slow-growing shaded specimens tend to lose apical dominance and may show poor stem form following deer nipping or frost injury to the terminal bud.

Green ash of sapling or pole size sprouts readily. The resultant sprout clumps usually contain several stems. Cuttings from one-year-old trees root rather easily under greenhouse conditions, but no practical way to root cuttings from older trees has yet been found.

Broadfoot (1969 has reported heights of 40-year-old green ash trees on bottom lands to range from 53 to 92 feet. On southern pine sites, growth is slower. A sample of 10 green ash trees (5.6 to 6.4 inches in dbh) collected from pine sites throughout the species' southern range averaged 37 years of age, 5.9 inches in dbh, and 47 feet in height (table 3-1).

ASH, WHITE (*Fraxinus americana* L.)

White ash is the largest, most common, and most useful of the American ashes. It occurs throughout the forested South except for parts of the lower Coastal Plain, and its range extends north into Canada.

White ash requires high soil fertility and moisture, and is most common on sites with high nitrogen and fairly high calcium levels. Its pH tolerance varies at least from 5.0 to 7.5. It reaches its best development on moderately well-drained soils, is rarely found in swamps, but is common on alluvium of smaller streams. On pine sites, it is most plentiful in moist situations such as the upper extremities of minor tributaries.

White ash ranges from near sea level in the Coastal Plain to about 3,500 feet in the Cumberland Mountains. In the Coastal Plain it is usually limited to the slightly elevated ridges in the bottoms of major streams. Rarely is white ash a common tree in the flat bottoms of major streams or in depressions where there is poor drainage.

White ash is **dioecious**; however, more male than female trees bloom. Open-grown vigorous trees may start to bloom when only 3 or 4 inches in diameter, but trees are usually 8 to 10 inches in diameter before flowering is abundant. Full bloom occurs before leaf buds start to enlarge. On male trees, 2 to 3 weeks elapse from the time there is a noticeable enlargement of winter buds until pollen shedding is complete. Pollen shedding of a single tree usually extends 3 or 4 days; that of a stand lasts 5 to 7 days. Most of the pollen, which is wind carried, travels only a few hundred feet. On female trees, buds are completely open a few days after they start to swell. The exposed flowers are receptive to pollination for about a week.

About half the flowering trees have abundant crops of seed; the rest bear almost none. Seed is dispersed up to 450 feet. Freshly collected seed is dormant and requires 2 to 3 months' moist stratification at refrigerator temperatures to germinate. Establishment of direct-seeded stands has proven difficult (Russell 1976).

Stumps of freshly cut seedlings and sapling white ash sprout readily. The sprout clumps usually contain several stems. This species is about as easy to propagate by conventional methods of budding or grafting as the common fruit trees. Even open-field and bench grafting of unpotted stock gives high percentages of success. There is no reliable method for rooting cuttings.

When young, white ash is shade tolerant, seedlings can survive and grow appreciably with less than 3 percent of full sunlight. With increasing age, white ash becomes less tolerant; it is usually ranked as intermediate-tolerant or intolerant. When judged by the rapidity of death of shaded branches, it is considered very intolerant. Ash is also intolerant of vines which deform the seedlings, reduce their growth, and prevent a single leader from dominating (Johnson 1971).

White ash can be maintained more easily in a dense stand than can some of its associates, such as northern red oak. Dominant or codominant white ash trees respond readily to thinning and within a few years wil increase crown area sufficiently to take full advantage of any reasonable increased growing space.

White ash is a pioneer species that seeds in on the more fertile abandoned fields in several parts of the country, but in the Southeastern States, much of the abandoned agricultural land is incapable of supporting the species. On such sites, it comes in only after some site protection and improvement has been accomplished by pines.

Throughout its range white ash is a minor but constant component of both the understory and overstory of mature forests on suitable soils. It owes its position in the final overstory to its ability to persist for a few years in moderately dense shade and to take quick advantage of any openings in the canopy created by death of an occasional old tree.

Open-grown trees commonly remain single stemmed and fine branched until they are 30 to 40 feet tall, although old specimens may develop broad crowns. With even slight crowding, the single-stemmed characteristic can easily be maintained throughout a rotation.

Because uninjured terminal buds suppress the growth of laterals on the current year's growth, each internode has only one pair of branches that persist more than a few years. There is little or no epicormic branching on the boles of released trees. Branches of dominant trees emerge from the bole at about a 35° angle from the vertical, whereas the branches of intermediate trees emerge at about a 55° angle.

Shade-killed branches drop quickly—small ones within a year or two and larger ones within 4 or 5 years.

Depending upon the amount of root competition, a white ash tree in full sunlight may take 3 to 15 years to reach breast height. Once it has reached this height, its root system is normally adequate for rapid growth even though surrounded by weeds. The post-juvenile growth rates of dominant trees in unthinned even-aged stands in central Massachusetts are shown in the following tabulation:

Age	Dbh	Height
Years	*Inches*	*Feet*
20	4	38
30	7	57
40	10	68
50	12	76
60	14	82
70	17	90

There are no yield tables for white ash in pure stands, nor are there data on the maximum growth rates attainable by individual trees over long periods of time.

A sample of 10 white ash trees (5.5 to 6.5 inches in dbh) collected from southern pine sites throughout the species' southern range averaged 40 years of age, 5.9 inches in dbh, and 50 feet in height (table 3-1).

ELM (*Ulmus* spp.)

Of the six species of elm native to North America, two—American (*U. americana* L.), and winged (*U. alata* Michx.)—are important in the South. American elm is best known and commercially most important. This species, together with the less abundant slippery elm (*U. rubra* Muhl.), provides the **soft elm** of the lumber trade (Chen and Schlesinger 1973).

Winged elm and, of lesser importance, cedar elm (*U. crassifolia* Nutt.) constitute the southern hard elms which compare favorably with the northern rock elm (*U. thomasii* Sarg.), a species favored for specialty uses (Baudendistal and Paul 1944).

Species descriptions in this text are limited to American and winged elm because of their importance in the South. Survey data, however, include all the elm species. Figure 3-3 shows the distribution of elm species Southwide on all sites.

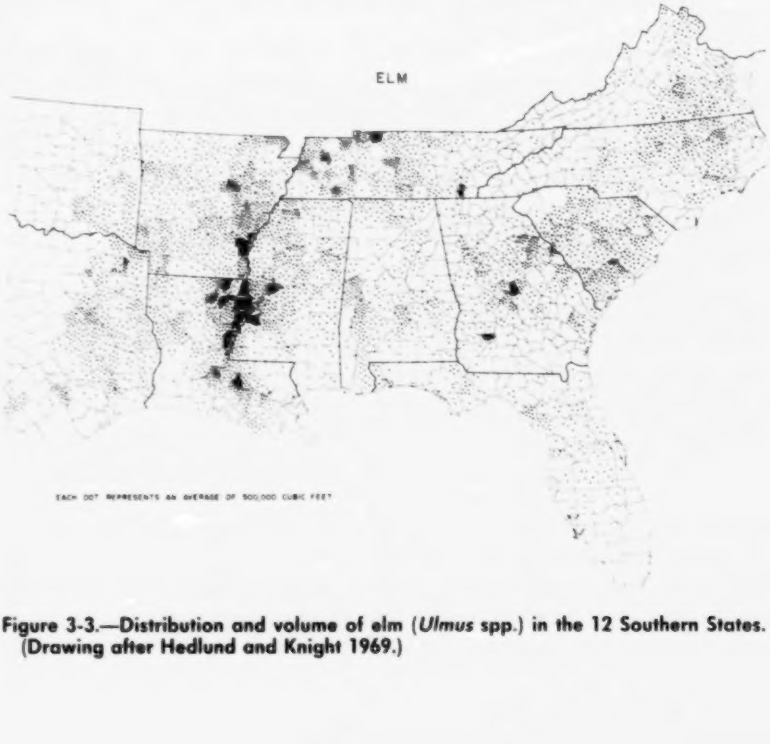

Figure 3-3.—Distribution and volume of elm (*Ulmus* spp.) in the 12 Southern States. (Drawing after Hedlund and Knight 1969.)

Twenty-five percent of total elm volume in the South is on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations are greatest in counties of Louisiana, Arkansas, and South Carolina (fig. 3-4), but total pine-site volumes of elm species are largest in Arkansas (102 million cubic feet), Mississippi (82), and Georgia (80). Texas, South Carolina, North Carolina, and Alabama have pine-site volumes of elm in the range from 63 to 71 million cubic feet, while Louisiana and Virginia have 47 and 43 million cubic feet. Florida, Oklahoma, and Tennessee have least volumes of elm on pine sites (4, 18, and 26 million cubic feet).

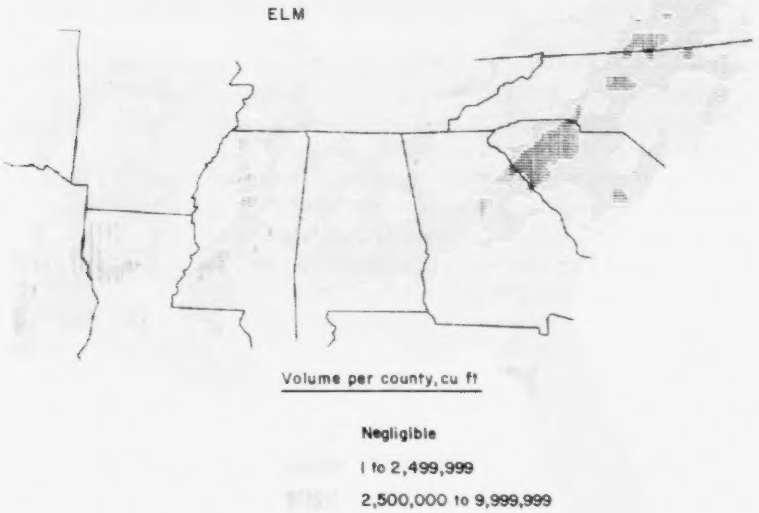

Figure 3-4.—SYMAP computer map of distribution and concentrations of elm (*Ulmus* spp.) on pine sites. (Drawing after Christopher et al. 1976.)

ELM, AMERICAN (*Ulmus americana* L.)

American elm is found throughout the forested South, its range embracing nearly all of eastern North America. It is common as far south as the Gulf Coast and central Florida.

American elm grows on soils ranging in texture from coarse sands to clays, but it does best on rich well-drained loams. Soil mixture regime may influence growth of this species more than soil texture alone. In the South, American elm is common on clay and silty-clay loams on first bottoms and terraces; growth is medium on wetter sites and good on well-drained flats in first bottoms. In shelterbelts American elm survives on uplands with sandy soils. On pine sites in the South its growth is best on minor drainages and other well-watered locations, but the species also occurs on sandy uplands. A soil pH from 5.5 to 8.0 is considered suitable for the species.

Seed production in American elm may begin in saplings 15 years old, but is seldom abundant before the trees are 40 years old; it then remains abundant until trees are 150 years old. In closed stands, seed production is greatest in the exposed tops of dominant trees. The winged seed are light and readily disseminated by the wind. Although most of the seed falls within 100 yards of the trees, some may be carried a quarter of a mile or more. Seeds usually germinate soon after they fall (generally in March in the South), although some seed may remain dormant until the following spring. American elm seedlings can withstand flooding in the dormant season, but will die if flooding is prolonged through the growing season.

Small American elm trees produce vigorous stump sprouts. The species can be propagated from cuttings, but results are variable. Cuttings taken in June and rooted with indolebutyric acid have been successful; leafbud cuttings have given results superior to softwood cuttings.

American elm is intermediate in tolerance among the eastern hardwoods. It usually responds well to release, often exhibiting better growth at advanced ages than its associates. Once it becomes dominant in a mixed hardwood stand, it is seldom overtaken by other species. It can persist for years as an intermediate, but it will die if suppressed by tolerant hardwoods.

Since American elm seldom grows in pure stands, there is little information available on yields. Dominant American elm may reach heights of over 100 feet on good sites, and heights of 80 feet are common on medium sites. However, on poor sites with very wet soils, or on the dry soils of the Plains, this species is often only 40 to 60 feet tall at maturity.

A sample of 10 American elm trees (5.5 to 6.3 inches in dbh) collected from southern pine sites throughout the species' southern range averaged 40 years of age, 5.9 inches in dbh, and 47 feet in height (table 3-1).

ELM, WINGED (*Ulmus alata* Michx.)

Winged elm is found principally in the southeastern United States, ranging westward from the borders of swamps and streams in southeastern Virginia, southwestern Indiana, southern Illinois to central Missouri. Southward it is found in eastern Oklahoma, east Texas, and eastward to central Florida.

Winged elm is found on a great variety of soils. It grows fairly well on dry as well as on rich, moist soils. Its best development is principally on loamy flats, as in the Mississippi River Delta. On the Delta bottom lands it occurs widely on terrace ridges and colluvial sites. Occasionally it occurs on high terrace flats with tight soils. Generally found along intermittent streams and other moist lower-slope sites, winged elm is rarely associated with persistent standing water. In the hill country of Tennessee and North Carolina, it may be found on upper or middle slopes. It is listed in forest types that occur at elevations up to 2,500 feet.

Conditions for satisfactory germination and survivial of winged elm seedlings have not been studied. One study shows that winged elm seedling development is best at one-half sunlight intensity. While one-half light intensity resulted in the greatest height growth of winged elm, American elm grew best at one-third light intensity. In flood-plain areas of the Delta region, reproduction is usually prolific in openings but occurs less frequently as an understory.

Winged elm is a medium-sized tree usually 40 to 50 feet in height but occasionally 80 to 100 feet, and it may be 1 to 1½ feet in diameter. This species develops a short bole with branches ascending into a fairly open, round-topped crown. It has a lacy, or somewhat drooping, habit. One special characteristic is the corky, persistent wings, or projections, often found on the branchlets. In the absence of natural stands of commercial importance, volume and yield values are not available. Winged elm in open shade-tree conditions grows rapidly, but under forest conditions its growth rate is usually considered poor in relation to its associates.

A sample of 10 winged elm trees (5.5 to 6.5 inches in dbh) collected from southern pine sites throughout the species' range averaged 49 years of age, 6.0 inches in dbh, and 45 feet in height (table 3-1).

HACKBERRY (*Celtis* spp.)

Hackberries, comprising about 70 species of trees and shrubs, are widespread in both tropical and north temperate regions. Of the seven species native to the United States, only two are important timber trees (U.S. Department of Agriculture, Forest Service 1965.) The most recent description of these hackberries is that of Smalley (1973), from which the following discussion is condensed.

In the lumber trade, the name hackberry is commonly applied to two closely related species—hackberry (*C. occidentalis* L.) and sugarberry (*C. laevigata* Willd.). Hackberry is the more northern species, its range extending into the South primarily in northern Oklahoma, Arkansas, and Tennessee. It occurs locally in Mississippi, central Alabama, and northern Georgia. Sugarberry ranges throughout the South except in the Appalachian Mountains (fig. 3-5).

Commercial use is predominantly of sugarberry. The better grades are used principally for furniture, and to a lesser extent millwork, and sporting and athletic goods. Low-grade lumber is made up largely into boxes and crates. Veneer is used mainly in the manufacture of containers and interior plywood faces.

The hackberries are straight-grained, sometimes interlocked-grained, moderately hard woods with a specific gravity (ovendry) of 0.59. The sapwood is wide and varies in color from pale yellow to grayish or greenish yellow, frequently discolored with blue sap stain. The heartwood, when present, varies from yellowish gray to light brown streaked with yellow. Growth rings and wood rays are distinctly visible to the naked eye.

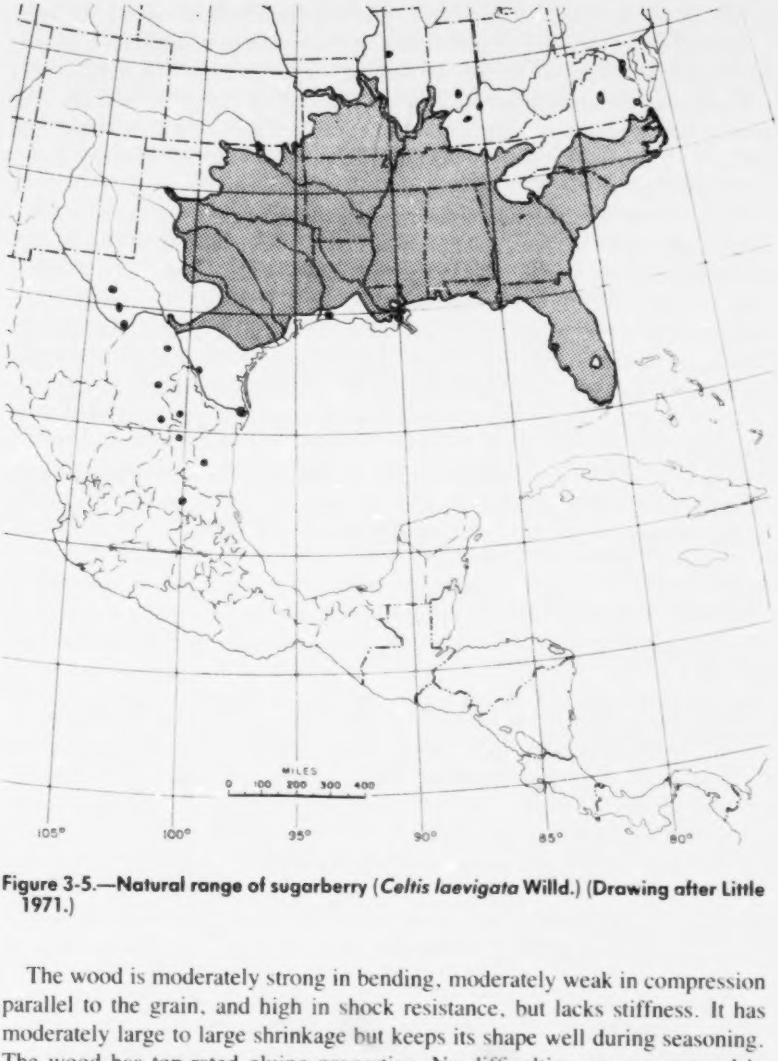

Figure 3-5.—Natural range of sugarberry (*Celtis laevigata* Willd.) (Drawing after Little 1971.)

The wood is moderately strong in bending, moderately weak in compression parallel to the grain, and high in shock resistance, but lacks stiffness. It has moderately large to large shrinkage but keeps its shape well during seasoning. The wood has top-rated gluing properties. No difficulties are encountered in planing hackberry and it also ranks high in turning properties. It is intermediate in nail- and screw-holding ability, and it resists splitting from screws better than from nails.

The light color of the wood permits furniture manufacturers to use light-to-medium brown finishes without bleaching, which is necessary on some other woods. The moderate grain pattern makes hackberry highly desirable for solid parts in furniture designed for fine face veneers on large flat surfaces.

Figure 3-5 shows the range of sugarberry. Survey data do not distinguish the hackberries; only 4.5 percent of total hackberry volume is on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations are greatest in a few counties of Texas and North Carolina (fig. 3-6); total pine-site volume is greatest in Texas (13 million cubic feet). Florida, Georgia, Louisiana, Mississippi, Oklahoma, Tennessee, and Virginia each have pine-site volumes of 4 million cubic feet or less. Arkansas, North Carolina, Alabama, and South Carolina have intermediate volumes (5, 6, 8, and 9 million cubic feet, respectively).

Hackberries grow on a wide variety of soils. They do best in rich, moist alluvial soils, but will grow on almost any soil and with little moisture. Throughout most of its range, hackberry is commonly found on slopes and bluffs and frequently on soils high in lime. It is drought resistant and consequently has been planted extensively in windbreaks in the Middle West. It will not tolerate sites with a permantly high water table. Sugarberry is most common on clay soils of broad flats or shallow sloughs within flood plains of major southern rivers, but will grow under a considerable range of soil and moisture conditions. It is also common on deep moist soils derived from limestone—notably in the Alabama Black Belt.

Both hackberry and sugarberry produce good seed crops most years and light seed crops in intervening years. Seed production of sugarberry starts when trees are about 15 years old. Optimum seed-bearing age is from 30 to 70 years. Comparable data for hackberry are not available. Average germinative capacity of hackberry seed is 41 percent, for sugarberry, 55 percent. The fruit ripens in

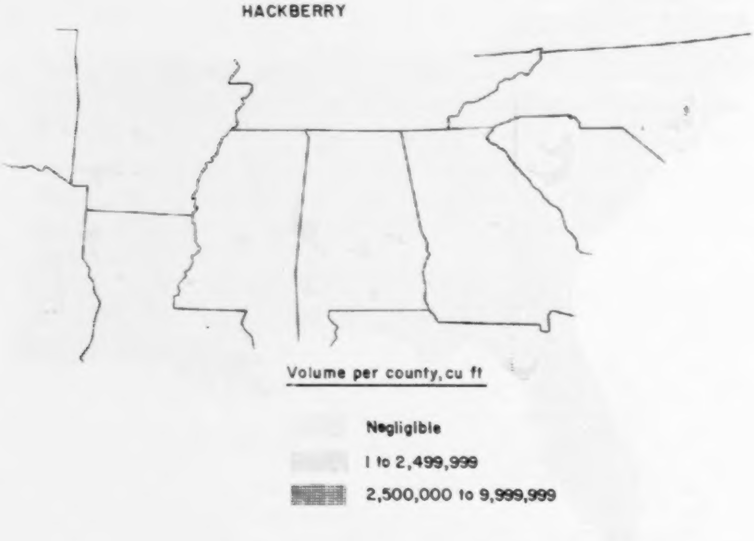

Figure 3-6.—SYMAP computer map of distribution and concentrations of hackberry (*Celtis* spp.) on pine sites. (Drawing after Christopher et al. 1976.)

September or October, and often remains on the tree until midwinter or later. There are between 1,580 and 2,380 cleaned hackberry fruits per pound and 2,000 to 2,400 for sugarberry. Seed is widely distributed by birds, less frequently by water.

Seed germinates early in the spring after lying on the ground over winter. The best natural conditions for germination are rich, moist, loamy soil. The two species are fairly tolerant in their ability to withstand shade. Early growth varies widely with the degree of competition. Under heavy overstory the height growth of hackberry may not exceed 1 inch per year while cultivated trees in shelterbelts average 1.3 feet per year during the first 6 years. First-year growth of sugarberry usually produces a very slender but tough stem 8 to 18 inches high. Under shade the stem is typically short, crooked, and often forked. In the open it will be limby and short. Sugarberry responds to release. In dense, even-aged stands it prunes itself well and produces a straight stem.

Both species can be propagated by cuttings. Sprouts develop from stumps of small trees and fire-damaged seedlings and saplings. Stumps of larger trees rarely sprout. Few stands are of sprout origin.

Mature hackberry is usually a small to medium-sized tree 30 to 50 feet tall and 18 to 24 inches in diameter. On best sites it may reach a height of 130 feet and a diameter of 3 to 4 feet. The trunk may be clear of branches for 30 feet or more. Annual diameter growth may be as much as ⅓ inch. On the average it is much less, particularly in the western part of the range. Diameter growth is most rapid between the 20th and 40th years. On poor sites growth is very slow and the tree is frequently of small size, sometimes only a shrub. Sugarberry is generally taller, often attaining a height of 80 feet at maturity. On best sites dominant sugarberry trees grow in excess of ¼ inch annually. The overall average in natural unmanaged stands is between 1/10 and 2/10 inch annually.

A sample of 10 hackberry trees 5.5 to 6.4 inches in diameter—probably mostly sugarberry—collected from southern pine sites throughout the range of sugarberry averaged 28 years of age, 6.1 inches in dbh, and 45 feet in height (table 3-1).

HICKORY (*Carya* spp.)

There are about 15 species of hickories, including the pecans. Eleven are native in eastern United States, eight are important in American forestry, and four are common on pine sites in the South.

Of these eight important hickories, half are known as true hickories and the others as pecan hickories, as follows:

True hickories
- Shagbark hickory, *C. ovata* (Mill.) K. Koch
- Shellbark hickory, *C. laciniosa* (Michx. f.) Loud.
- Pignut hickory, *C. glabra* (Mill.) Sweet
- Mockernut hickory, *C. tomentosa* Nutt.

Pecan hickories
- Pecan, *C. illinoensis* (Wangenh.) K. Koch
- Water hickory, *C. aquatica* (Michx. f.) Nutt.
- Nutmeg hickory, *C. myristicaeformis* (Michx. f.) Nutt.
- Bitternut hickory, *C. cordiformis* (Wangenh.) K. Koch

Pecan hickories are distinguished by characteristics of their buds, which are naked or with four to six valvate scales with edges that do not overlap; true hickories have buds with more than six overlapping scales (Preston 1970). The wood of the pecan hickories is rated as strong, stiff, very hard, heavy, and very high in shock resistance. In strength, mechanical properties, and shock resistance, it is rated below the wood of the true hickories, but somewhat above white oak (*Q. alba* L.), sugar maple (*A. saccharum* Marsh.) and white ash (*F. americana* L.)

True hickories have traditionally been used for handles of striking and lifting tools such as hammers and shovels. The wood of pecan hickories finds use in furniture, flooring, paneling, plywood containers, baseball bats, skiis, and archery equipment. Hickory is also used for fuel, charcoal, and chips that impart a smokey flavor to barbecued foods.

The true hickories are principally components of oak-hickory forests, although some species occur in the beech-maple and bottomland hardwood types. The pecan hickories, with the exception of some bitternut hickory, are usually found in bottomlands or areas adjacent to them (Nelson 1965).

The hickories are present as a consistent component throughout the 116-million-acre oak-hickory forest, the most extensive forest type in the United States. Best developed and most continuous in the Ozark and Ouachita Highlands, this forest occurs on all upland sites from the driest ridges to the coolest slopes and protected coves (Watt et al. 1973).

Figure 3-7 shows the distribution of sawtimber volume of *Carya* species by state. In 1956, Kentucky contained more hickory than any other state—2.9 billion board feet. Louisiana ranked next with about 2 billion feet, chiefly pecan growing in the bottomlands along the Mississippi River. Together these two states contained 22 percent of the total supply of hickory sawtimber (Cruikshank and McCormack 1956).

Forty-eight percent of total hickory volume in the South is on pine sites (tables 2-7 through 2-18). Certain counties in 10 of the 12 Southern States have pine-site concentrations of hickory exceeding 10 million cubic feet in trees 5 inches in dbh or larger; Texas and Florida are the exceptions (fig. 3-8). Total pine-site volumes of hickory are largest in Alabama (850 million cubic feet). Arkansas, Georgia, Mississippi, North Carolina, Tennessee, and Virginia have pine-site volumes of hickory in the range from 356 to 518 million cubic feet. Florida, Oklahoma, Texas, and Louisiana have least volumes of hickory on pine sites (37, 88, 155, and 197 million cubic feet).

As a group, hickories are slow growers. In one report of ten-year diameter growth in the Central States, saplings, poles, and sawtimber ranged from 0.70 to 1.44 inches; the average for all three classes was 1.26 inches (Nelson 1965).

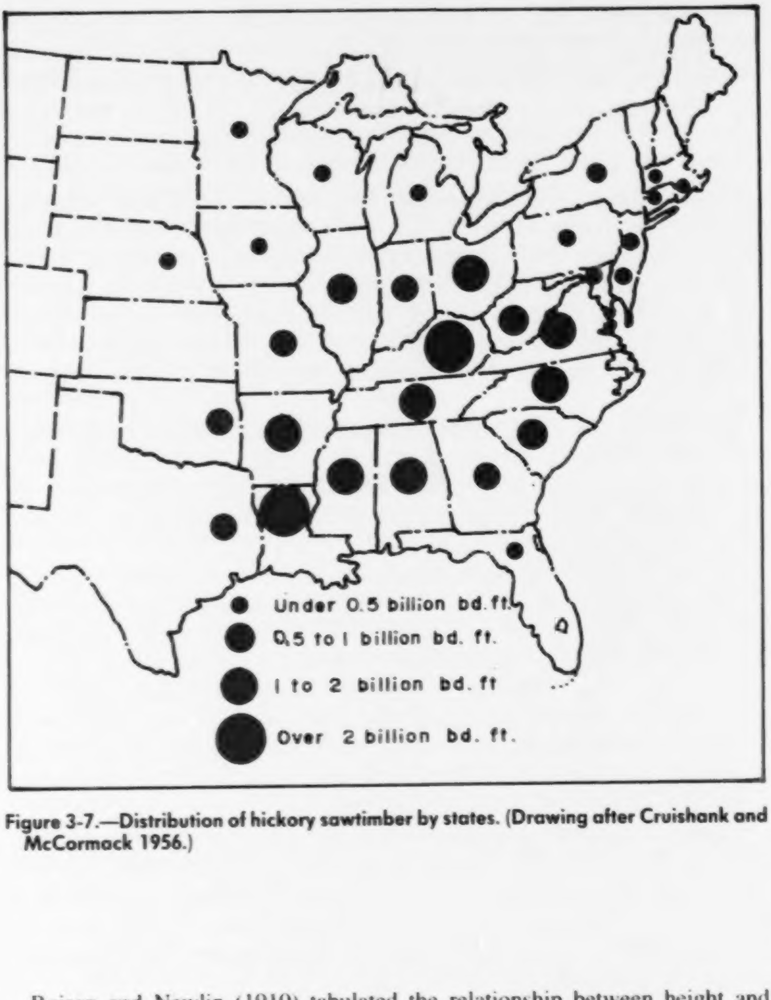
Under 0.5 billion bd. ft.
0.5 to 1 billion bd. ft.
1 to 2 billion bd. ft
Over 2 billion bd. ft.

Figure 3-7.—Distribution of hickory sawtimber by states. (Drawing after Cruishank and McCormack 1956.)

Boisen and Newlin (1910) tabulated the relationship between height and merchantable length of hickory in low-density stands, as follows:

Dbh	Tree height	Length of merchantable bole
Inches	*Feet*	
6	*43*	*8*
8	*56*	*12*
10	*67*	*16*
12	*77*	*19*
14	*86*	*22*
16	*95*	*25*
18	*102*	*28*

In dense stands, merchantable boles would be longer.

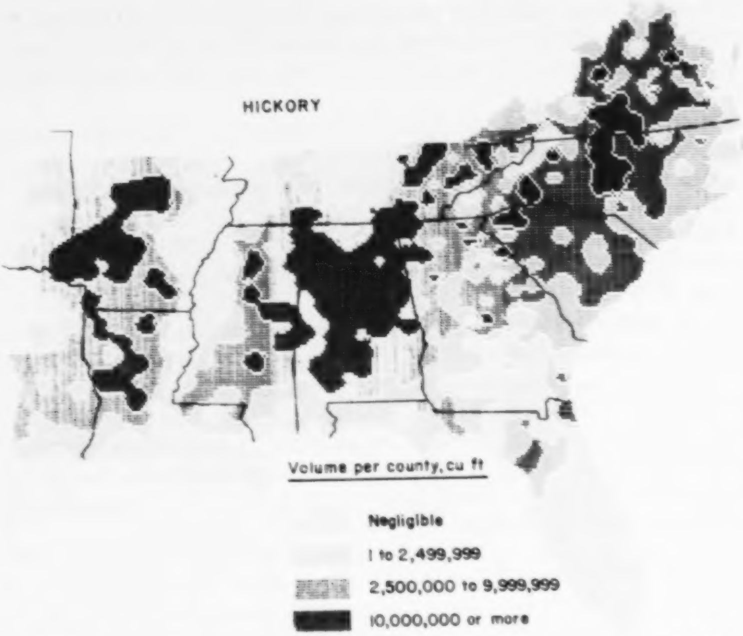
HICKORY
Volume per county, cu ft
Negligible
1 to 2,499,999
2,500,000 to 9,999,999
10,000,000 or more

Figure 3-8.—SYMAP computer map of distributions and concentrations of hickory (*Carya* spp.) on pine sites. (Drawing after Christopher et al. 1976.)

In a sample of 700 hickory trees measuring 4 inches in diameter, Boisen and Newlin (1910) observed that their age averaged 30 years; other age-diameter-height relations they observed in samples of 40 to 120 trees per age class were as follows:

Tree age	Dbh	Tree height
Years	*Inches*	*Feet*
40	5.0	41
50	6.2	49
60	7.2	57
70	8.1	64
80	9.0	69
90	9.8	74
100	10.5	78

Hampf (1965) has related height of hickory trees to age and site index (tree height in feet at age 50) as follows:

	Tree height at two ages	
Site index	20 years	100 years
Feet	----------*Feet*----------	
30	*16*	*47*
50	*19*	*78*
70	*28*	*110*
90	*34*	*140*

On southern pine sites, growth is very slow. A sample of 10 hickory trees (5.6 to 6.5 inches in dbh) collected from pine sites throughout the species' southern range averaged 55 years of age, 6.0 inches in dbh and 45 feet in height (table 3-1).

In most years, essentially all hickory (and oak) seeds are destroyed by insects, fungi, birds, or mammals. When the infrequent bumper crop is produced, enough seed escapes damage to provide abundant seedling reproduction. If hickories (and oaks) are especially desired in a stand, but advance reproduction of them is inadequate, no final harvest cut should be made; cutting should be deferred, or light thinning used to promote advance regeneration (Watt et al. 1973).

In the species descriptions that follow in this chapter and elsewhere, shellbark hickory is omitted because its range is principally in the Mid-West north of the 12 Southern States, with only limited intrusions into Arkansas and Tennessee. Also omitted are nutmeg, pecan, and water hickories which are bottom land species of little importance on southern pine sites. Readers desiring additional information on the identification, range, and silviculture of these four species should consult Caldwell (1953), Bishop and Nelson (1955), Nelson (1965), USDA Forest Service (1965), and Clark (1973).

HICKORY, BITTERNUT (*Carya cordiformis* (Wangenh.) K. Koch)

Bitternut hickory is probabaly the most abundant and uniformly distributed of the hickories. It is found through the forested South except along the Gulf and most of the Mississippi Delta, and ranges north into Canada. It is one of the hickories least susceptible to frost damage.

In the southern part of its range, bitternut is more restricted to moist sites than in the northern part. It is not found at the highest elevations in the Appalachians. It reaches its largest size on the rich bottomlands of the Lower Ohio River Basin. In the southeastern part of its range, it occurs only on overflow bottoms. In the southwestern part, however, it is common on poor, dry, gravelly, upland soils.

Bitternut hickory does not produce abundant seed until the tree is approximately 30 years old. Optimum production extends from 50 to 125 years. Good seed crops appear at 3- to 5-year intervals, with light seed crops borne in the intervening years. Bitternut hickory seed is estimated to be from 70 to 85 percent viable. Seed dissemination is almost entirely by gravity—the fruit is thought to be generally distasteful to wildlife. Since bitternut grows in wet bottom land, floodwaters probably influence its seeding range. Bitternut is probably more tolerant of a moist seedbed than are the other hickories.

Bitternut hickory is reported to sprout more vigorously than other hickories. In one study, the average height of dominant 1-year-old sprouts was 4.7 feet. Sapling and pole-size trees sprout mostly from the root collar, sawtimber-size trees from the root. Stump sprouts are usually less numerous than either root-collar sprouts or root sprouts.

Bitternut hickory is easily damaged by fire, especially when young. Fire wounds are the principal pathway for entry of heart-rot fungi in this and other hickories.

HICKORY, MOCKERNUT (*Carya tomentosa* Nutt.)

Mockernut hickory grows throughout the South except in southern Florida and parts of the Mississippi Delta. Its range extends north to New England and southern Ontario. It is abundant in the lower Mississippi Valley and reaches its largest size in the Lower Ohio River Basin and in Missouri and Arkansas. Mockernut is the only hickory found in the pine forests of the sandy pine belt of the Southern States.

Mockernut hickory requires a minimum of 25 years to reach commercial seed-bearing age. Optimum production occurs from 40 to 125 years, and the maximum age for commercial seed production is 200 years. Good seed crops occur every 2 to 3 years, with light seed crops in intervening years. Approximately 50 to 75 percent of fresh seed will germinate. Mockernut hickory, although seldom cultivated for fruit production, produces sweet, tasty nuts that are eaten by humans, and the fruit forms a part of the diet of raccoons, squirrels, and chipmunks. Mockernut is one of the heaviest seeded species of *Carya*, averaging 90 seed per pound. The seed is disseminated mainly through gravity and by squirrels. Hickories, in general, require a moderately moist seedbed for satisfactory seed germination, and mockernut appears to reproduce best in moist duff. Young mockernut seedlings are very susceptible to damage by frost.

Most of the merchantable mockernut grows on moderately fertile uplands; it attains its best development only on deep fertile soils. In the Cumberland Mountains and the hills of southern Indiana, it grows on dry sites, such as south and west slopes or dry ridges. Stunted mockernut grows in Alabama and Mississippi on the sandy shortleaf and loblolly pine land. The species is also found as a dwarf along with yaupon (*Ilex vomitoria* Ait.) and live oak (*Quercus virginiana* Mill.) in the sand dunes of South Carolina.

HICKORY, PIGNUT (*Carya glabra* (Mill.) Sweet)

Pignut hickory occurs throughout the South except for southern Florida, the Mississippi Delta, Oklahoma, and parts of eastern Texas. Its range extends north into the Lake States and southern New England.

This species is best developed in the Lower Ohio River Basin. It is the hickory most commonly found in the Appalachian forest and probably furnishes most of the hickory cut in the Cumberland Mountains of Tennessee, Kentucky, and West Virginia, and the hill country of the Ohio Valley.

Pignut hickory generally inhabits dry ridges and hillsides with well-drained upland soils; however, it responds readily to increases in soil fertility.

Pignut hickory begins to bear seed in quantity at 30 years, with optimum production occurring from 75 to 200 years. The fruit ripens in September and October, and seeds are dispersed from September through December. Good seed crops occur every year or two, with light crops in other years. Fifty to seventy-five percent of fresh pignut hickory seed will germinate. They are lighter than other hickory seeds, averaging 200 to the pound. Seeds are disseminated principally by gravity, but squirrels and chipmunks extend the seeding range. Establishment appears to be favored by duff and litter.

Pignut hickory as a seedling and as an older tree tends to develop a pronounced taproot with few laterals. This is true even in soils unfavorable for taproot development. Although pignut hickory sprouts prolifically from stumps, it is difficult to reproduce from cuttings.

On both dry and moist sites of the Southern Appalachian region, pignut hickory will produce sawtimber, but in the longleaf pine-turkey oak associates of the southern pine regions it does not reach saw-log size. Its value for sawtimber is often diminished by a forked bole. It is classed as tolerant in the Southeast, and is a climax species in oak-hickory stands throughout most of its range.

Pignut hickory is easily damaged by frost and fire. Such injuries cause degrade or loss of volume, or both. Much degrade in Appalachian hickory results from sapsucker injury.

HICKORY, SHAGBARK (*Carya ovata* (Mill.) K. Koch)

Shagbark hickory occurs throughout the upper South, but is scarce or absent in most of the lower Coastal Plain, the Mississippi Delta, and parts of eastern Texas and Oklahoma. Its range extends into Canada, and it is found in scattered localities in Mexico.

Sites occupied by shagbark hickory vary greatly over its range. In the North, this species grows on upland slopes at elevations as high as 2,000 feet. Farther south it is more prevalent on deep, moist soils of alluvial origin. In the Ohio Valley, it grows chiefly on north and east slopes of fertile uplands; in the Cumberland Mountains, it is confined to coves and to north and east slopes; and in Arkansas, Mississippi, and Louisiana, it grows principally on bottoms along rivers and minor streams.

Shagbark hickory reaches commercial seed-bearing age at 40 years; optimum seed-bearing age is 60 to 200 years. The fruits ripen in September and October, and the sweet nuts are dispersed from the dehiscent husks from September through December. Good seed crops occur at 1- to 3-year intervals, and light seed crops in intervening years. The germination of fresh seed is 50 to 75 percent. Shagbark nuts are heavy, about 100 per pound, and are disseminated by gravity, squirrels and chipmunks.

Hickories require a moderately moist seedbed for satisfactory seed germination and early establishment. To promote germination, shagbark hickory nuts should be stored at 3°C and 5-percent seed moisture. Fresh nuts and those stored up to 2 years need 90 to 120 days of stratification; stratification should be reduced to 60 days for nuts stored over 2 years (Bonner 1976). Shagbark seedlings produce a long taproot early in their development.

The species is classified as moderately tolerant and suppressed trees recover rapidly when released. It is usually a climax species in the timber types in which it occurs.

Shagbark hickory sprouts prolifically, especially from small stumps; larger stumps produce fewer stump sprouts and more root suckers.

Shagbark hickory at all ages is highly susceptible to fire damage. Heart rot fungi enter fire wounds and cause progressive wood loss.

MAPLE, RED (*Acer rubrum* L.)

In the lumber trade, red maple together with silver maple (*A. saccharinum* L.) and box elder (*A. negundo* L.), is sold as **soft maple.** In the forest, red maple is distinguished from the other soft maples by its bright red spring flowers which are followed by winged seed even more intensely red; autumn coloration of the foliage is red, and in winter the twigs appear smooth, shiny, and red.

The sapwood of the silver maple is lighter in color than that of red maple although both are described as "white." Heartwood in red maple is slightly darker than the others, each one varying somewhat from a pale tan to reddish gray. These species average about two-thirds as hard as sugar maple (*A. saccharum* Marsh.). Soft maple is much used for furniture manufacture because it resembles sugar maple, machines easily and is less costly. Soft maple stays in place well, and is glued without difficulty; also, it can be steam bent successfully. Cf 11 hardwoods tested to determine their freedom from odor and taste, soft maple ranked second best, with ash heading the list (Southern Hardwood Lumber Manufacturers' Association (n.d.a, b)).

In the South, the soft maples are most heavily concentrated in the easternmost states north of Florida (fig. 3-9). In the Mississippi Delta Region, about 70 percent of the production of soft maple lumber is red maple, 25 percent silver maple, and 5 percent box elder (Southern Hardwood Lumber Manufacturers' Association (n.d.a, b)). Red maple is found throughout the forested South and its range extends to the north well into Canada. It reaches its best development in the mountains of Kentucky, Tennessee, and nearby states. A variety, Drummond red maple (*A. rubrum* var. *drummondii* (Hook. & Arn.) Sarg.) found in the lowlands of the Atlantic Coastal Plain and the Mississippi and Ohio Valleys is recognized by botanists. Although red maple grows in northern as well as southern latitudes, it ranks low in resistance to ice and snow damage.

Red maple occupies a wide variety of soils including podzols, gray-brown and red and yellow podzolics, bogs, alluvium, and lithosols. It occurs on soils derived from granites, gneisses, schists, sandstones, shales, slates, conglomerates, quartzites, and limestone.

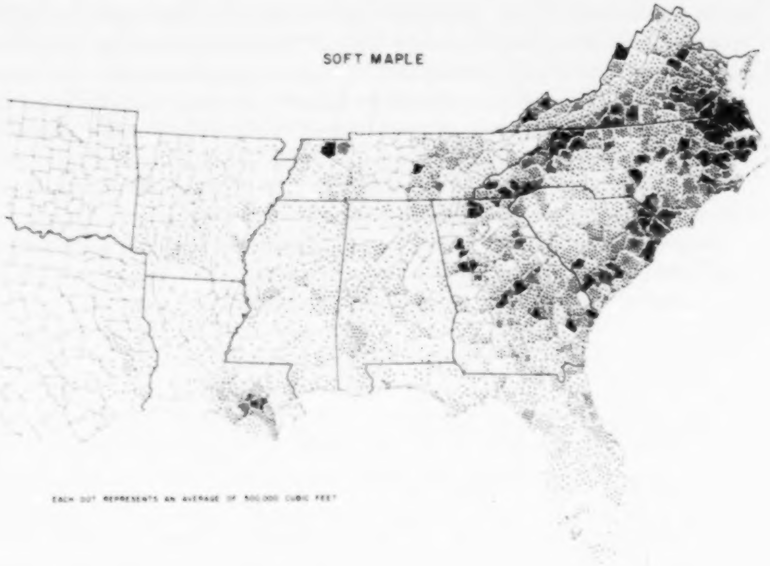

Figure 3-9.—Distribution and volume of soft maples (*Acer rubrum* L. and *Acer saccharinum* L.) in the 12 Southern States. (Drawing after Hedlund and Knight 1969.)

Even though this represents a wide variety of soil textures and soil-moisture conditions, red maple is common where the soil-moisture conditions are extreme—either very wet or quite dry.

Red maple is a poor soil-builder. Its litter is low in nitrogen and only intermediate in calcium in comparison with the litter of other trees.

Although this species reaches its best development on moderately well-drained moist sites at low to intermediate elevations, it is common in mountain country on the drier ridges and on south and west exposures of upper slopes. It is also common in swampy areas, on slow-draining flats and depressions, and along small sluggish streams. In the South, commercial harvests are mainly from bottom land.

About 33 percent of total red maple volume in the South is on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations are greatest in a band of counties in North Carolina and Virginia (fig. 3-10). Total pine-site volume of red maple is greatest in North Carolina (502 million cubic feet) followed by Virginia (384 million cubic feet) and Georgia (244 million cubic feet). Alabama, Tennessee and South Carolina have volumes of 126, 147, and 153 million cubic feet. States with pine-site volume from 23 to 53 million cubic feet include Florida, Texas, Arkansas, Louisiana, and Mississippi. Oklahoma has only 2 million cubic feet of red maple growing on pine sites.

A good seed crop occurs almost every year. The fruit, a **samara** (winged seed), ripens from March to late June, depending upon location. The dispersal

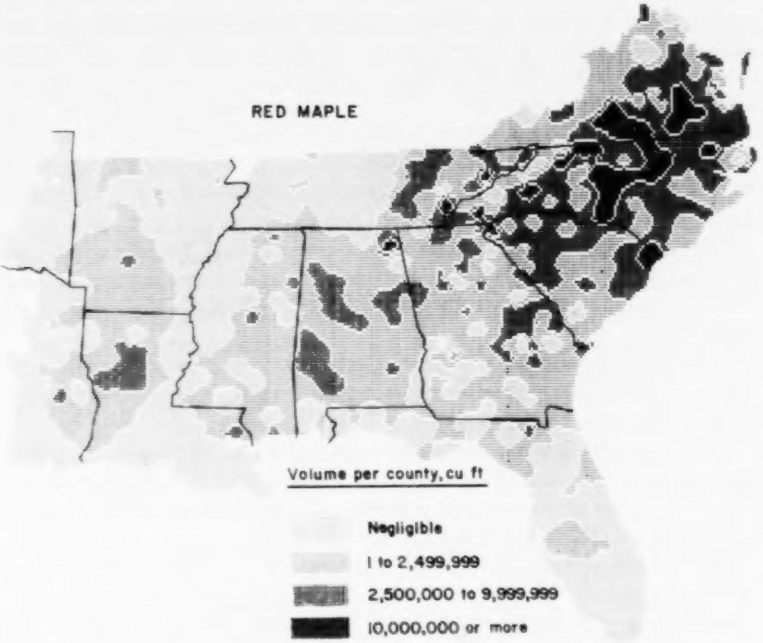

Figure 3-10.—SYMAP computer map of distribution and concentrations of red maple (*Acer rubrum* L.) on pine sites. (Drawing after Christopher et al. 1976.)

period is about 1 to 2 weeks, occurring sometime between April and July. Red maple seed is the lightest of all maple seed, averaging about 23,000 to the pound. It is disseminated by wind. Most red maple seeds germinate in early summer soon after falling, but a few lie over until the following spring. They do not need much light to germinate. A thin layer of hardwood leaf litter is no impediment to germination if the underlying soil is moist and mellow.

Seedlings on wet sites form short taproots with long, well-developed laterals. On dry upland sites, they produce deeply penetrating taproots and much shorter laterals; the taproot may reach a depth of 10 to 12 inches the first year.

In one study, newly germinated red maple seedlings were stunted but not killed when grown in saturated soils for periods up to 32 days; upon removal from saturation, they recovered rapidly.

With favorable light and moisture conditions, the seedlings make fast vigorous growth—as much as 1 foot the first year, and up to 2 feet or more annually during the next few years. A study in the Piedmont indicated that very young red maple seedlings require more light than those of yellow-poplar, but less than those of loblolly pine.

Red maple is a vigorous sprouter. Many of the second-growth stands in the Appalachian Mountains include a large proportion of red maple sprouts. The multiple sprouts grow rapidly at first but soon lose early vigor as competition increases. Many of them develop butt rot at the base.

Red maple is considered difficult to propagate from cuttings. Fair, but variable, rooting results from 3-hour soaking of cuttings in 200 mg/l of idolebutyric acid. Cuttings root best if taken in June, from the lower part of the crown, and from male clones or from female clones that are fruiting sparingly.

Under ideal conditions, red maple trees may reach a height of 120 feet and a diameter of 5 feet. Average mature trees, however, are 60 to 90 feet in height and 1½ to 2½ feet in diameter. It is a short-to-medium-lived tree, seldom living longer than 150 years.

Growth is rapid during early life, particularly during the pole stage; later, growth often is not well sustained. In managed, well-stocked, bottomland hardwood stands, an average diameter growth of 3 to 3½ inches in 10 years should be possible.

A study of radial growth in the Georgia Piedmont showed that red maple started its growth late in the season. Once growth began, it was half completed in 50 to 59 days and fully completed in 70 to 79 days.

Since red maple is usually found in mixed stands, no information is available about its potential yields. However, in the Appalachians, it is found in mixture on a wide variety of sites ranging in productive capacity from less than 2,000 to as much as 14,000 board feet per acre in 50 years.

On southern pine sites the species grows slowly. A sample of 10 red maple trees (5.5 to 6.1 inches in dbh) collected from pine sites throughout the species' southern range averaged 40 years of age, 5.8 inches in dbh, and 50 feet in height (table 3-1).

Red maple is usually considered a pioneer or subclimax species. On the better of the sites occupied by Virginia pine in Pennsylvania, red maple is the most common understory hardwood.

Red maple responds well to thinning. In a study in the Canadian Maritimes a 35-year old fire stand of coppice red maple was thinned by reducing each sprout clump to one of the better stems. The number of stems per acre was reduced from 1,057 to 227 and the cubic-foot volume from 1,071 to 408. Ten years later the 227 trees had more than doubled their volume (911 cubic feet per acre). In another study, a partial cutting was made on a 40-year-old stand of Allegheny northern hardwoods. Of all the species, red maple made the best growth. In the 10-year period after cutting, dominant red maple trees grew an average of 2.25 inches in diameter.

On poor sites red maple is apt to have poor form and considerable defect. In northeastern Pennsylvania, the average cull ranged from 13 percent in 12-inch trees to 46 percent in 24-inch trees. Red maple is especially sensitive to wounding, healing slowly because of the dying back of cambium surrounding the wound. Callus growth, when established, is reasonably rapid, but an extra year or two is required to make up the area lost by dieback.

Red maple is very susceptible to fire injury, and even large trees can be killed by moderate fires. The fire-killed trees sprout vigorously, however, and the species may become a more important stand component after a fire than it was before.

Because red maple is a preferred deer food, it is subject to much damage where these animals are abundant. Reproduction may be almost completely suppressed in areas where deer populations are excessive.

OAK (*Quercus* spp.)

The oaks are the most important, most abundant, and most widespread hardwood trees in the North Temperate Zone. They constitute about one-third the hardwood volume in the United States, and yield hardwood timber and veneers of excellent quality with outstanding beauty of grain and figure. Oak wood is strong, hard, and tough; additionally it has good machining and bending characteristics. It is used extensively for furniture, flooring, paneling, railroad crossties, and cooperage (Cooper and Watt 1973).

In the North Temperate Zone, there are about 300 oak species, about 58 of which are of tree size and occur in the United States. Twelve of the native tree species are important in pine sites in the South; eight others are important in the region, but are mainly limited to hardwood sites.

The 20 native oaks are classified into two subgenera, the red and the white oaks. **Red oaks**, sometimes termed black oaks, (subgenus *Erythrobalanus*) have leaves with apex and lobes bristle-tipped, acorns maturing the second year, bark usually blackish and furrowed, and heartwood porous with vessels open. Pores in red oak latewood (summerwood) are few and can be counted under a hand lens. Annual rings are usually wide. Heartwood has a reddish tinge and is not particularly durable under conditions favoring decay. Freshly cut red oak has a sour, often unpleasant odor.

The red oak group also includes nonlobed species such as water, laurel, and willow oak, (*Q. phellos* L.) which usually have entire margins and no bristles; blackjack oak leaves usually lack lobes or bristles, but leaves with terminal lobes occasionally occur and may have one bristle per lobe.

Eleven of the red and black oaks are important in the South; all are deciduous. Three of these species, marked with an asterisk in the following tabulation, have been designated **select** red oaks because of the quality of their wood and the volume in which they are produced (Cooper and Watt 1973); their Southern-State distribution and volume are mapped in fig. 3-11.

Scientific name	Common name
Q. Coccinea Muenchh.	Scarlet oak
Q. falcata Michx. var. *falcata*	Southern red oak
*Q. *falcata* Michx. var *pagodaefolia* Ell.	Cherrybark oak
Q. laurifolia Michx.	Laurel oak
Q. marilandica Muenchh.	Blackjack oak
Q. nigra L.	Water oak
Q. palustris Muenchh.	Pin oak
Q. phellos L.	Willow oak
*Q. *rubra* L.	Northern red oak
*Q. *shumardii* Buckl.	Shumard oak
Q. valutina Lam.	Black oak

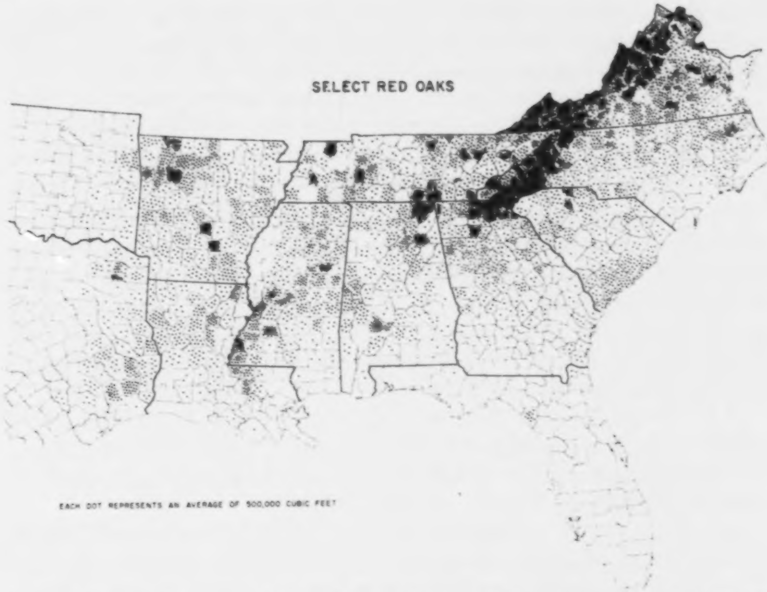
SELECT RED OAKS
EACH DOT REPRESENTS AN AVERAGE OF 500,000 CUBIC FEET

Figure 3-11.—Distribution of select red oaks (*Quercus falcata* var. *pagodaefolia* Ell., *Q. rubra* L., and *Q. shumardii* Buckl.) in the 12 Southern States. (Drawing after Hedlund and Knight 1969.)

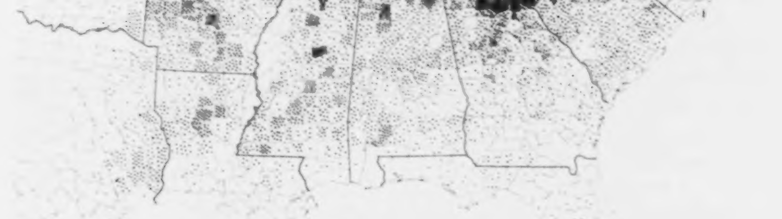
SELECT WHITE OAKS
EACH DOT REPRESENTS AN AVERAGE OF 1,000,000 CUBIC FEET

Figure 3-12.—Distribution and volume of select white oaks (*Quercus alba* L., *Q. bicolor* Willd., *Q. durandii* Buckl., *Q. macrocarpa* Michx., *Q. michauxii* Nutt., and *Q. muehlenbergii* Engelm.) in the 12 Southern States. (Drawing after Hedlund and Knight 1969.)

Nine of these eleven red oaks (pin oak and willow oak are the exceptions) are important components of pine-site hardwood volumes.

The **white oaks** (subgenera *Lepidobalanus*) have leaves with apex and lobes not bristle-tipped, acorns maturing the first year and bark usually light gray and scaly. Heartwood of white oak is less porous than that of red oak, the vessels usually being closed by outgrowths termed **tyloses**; chestnut oak, a white oak, is an exception in that its vessels are relatively free of tyloses. White oak heartwood is tan or brownish and usually lacks the red tinge characteristic of red oak heartwood. It is more decay resistant than heartwood of red oaks and ranks about equal in decay resistance to the heartwoods of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) or old-growth southern pine (e.g., *Pinus palustris* Mill.). Pores in latewood are numerous and so small that they usually cannot be counted, even with a hand lens. Also, the annual rings are compact so that the texture of white oak is usually finer than the more coarse textured red oaks. Freshly cut wood has a distinct, but not unpleasant odor.

Nine of the white oaks are of commercial importance in the Eastern United States; all but one (*Q. virginiana* Mill.) are deciduous. Five of the nine species, marked with an asterisk in the following tabulation, have been designated **select** white oaks because of the quality of their wood and the volume in which they are produced (Cooper and Watt 1973); their Southern-State distribution and volume are mapped in fig. 3-12.

Scientific name	Common name
*Q. alba L.	White oak
**Q. bicolor* Willd.	Swamp white oak
Q. lyrata Walt.	Overcup oak
**Q. macrocarpa* Michx.	Bur oak
**Q. michauxii* Nutt.	Swamp chestnut oak
**Q. Muehlenbergii* Engelm.	Chinkapin oak
Q. prinus L.	Chestnut oak
Q. stellata Wangenh.	Post oak
Q. virginiana Mill	Live oak

Three of these white oaks (white, chestnut, and post) are important components of pine-site hardwood volumes. In aggregate, the red and white oaks comprise about half of the hardwood inventory on pine sites in the South.

On pine sites, well-stocked stands of oak grow slowly. As noted in chapter 2, 30-year-old, second-growth upland oak on an average site with 84 square feet of basal area yielded 10.35 cords of merchantable stem to a 4-inch top outside bark; this amounts to 0.34 cords (29 cubic feet of wood) per year (Schnur 1937, p. 8).

There is a voluminous literature on the silvics of the oaks. The reader wishing more detailed information than is provided by the 12 species descriptions of this text may find the following publications useful.

Silviculture, general
- Core 1971
- Trimble 1975
- U.S. Department of Agriculture, Forest Service 1965
- U.S. Department of Agriculture, Forest Service 1970

- Genetics
  - Ledig et al. 1971
  - Webb 1970
- Regeneration and sprouting
  - Clark 1970
  - Clark and Watt 1971
  - Merz and Boyce 1956
  - Mignery 1975
  - Olson and Boyce 1971
  - Russell 1971
  - Woods and Cassady 1961
- Yield and soil-site relationships
  - Arend and Julander 1948
  - Broadfoot 1969, 1976
  - Carmean 1971b
  - Evans et al. 1975
  - Graney and Bower 1971
  - Judson 1965
  - McIntyre 1933
  - Schnur 1937
  - Smalley 1967
  - Trimble and Weitzman 1956
  - Wiant et al. 1975
  - Yawney 1964
- Thinning
  - Allen and Marquis 1970
  - Carvell 1971
  - Clark and Liming 1957
  - Dale 1972
  - Gingrich 1971a, 1971b

OAK, BLACK (*Quercus velutina* Lam.)

Black oak is found in nearly all upland hardwood forest types and in some pine types east of the Great Plains. It occurs throughout the South except the lower Coastal Plain and parts of the Mississippi Delta. In the North, its range extends into Canada and New England.

Black oak in the South is commonly found on dry, sandy or rocky ridges, and on upper slopes, although it grows best on lower slopes and coves in this region. It grows on drier sites than white and northern red oaks, but does not thrive where post and blackjack oaks commonly grow. In the Ozarks, black oak is found on upper slopes and ridges where it tends to replace shortleaf pine on heavily cutover areas.

In the Southern Appalachian Mountains, black oak grows at elevations up to 4,000 feet, and is an important tree in the foothills. The largest trees of the species are found in the lower valley of the Ohio River.

Young black oak trees characteristically develop long taproots, which is perhaps why they survive on dry sites. These taproots sometimes do not persist on the better sites.

Black oak is an associate tree in a great many forest types; it may also grow in pine stands. It commonly occurs with the hickories, with post, scarlet, southern red, blackjack, and chestnut oaks, and with white and northern red oaks. In the South it is found with shortleaf pine, and occasionally in the second-bottoms, where it shares the highest and best-drained areas with loblolly pine, southern red oak, and sweetgum.

About 55 percent of total black oak volume in the South is found on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations are greatest in counties of northern Arkansas, northern Alabama, eastern Tennessee, and west central Virginia (fig. 3-13). Total pine-site volumes of black oak are greatest in Arkansas, Virginia, and Tennessee (353, 337, and 333 million cubic feet, respectively). Georgia, North Carolina, and Alabama have volumes of 188, 219, and 255 million cubic feet. Louisiana, Texas, Oklahoma, South Carolina, and Mississippi have pine-site volumes of 19, 53, 78, and 94 million cubic feet. Florida has no surveyed volume of black oak.

Acorns of black oak, growing solitary or in pairs, mature in 2 years. They ripen during September or October and generally drop before December. Black oak is a consistent seed producer, with good crops of acorns every 2 or 3 years. In Missouri, the average number of mature acorns per tree generally was higher than for other oaks over a 5-year period, but the number of acorns varied greatly by years and by trees within the same stand. Black oaks begin to produce seed at about 20 years, and reach optimum production at 40 to 75 years. Sound and

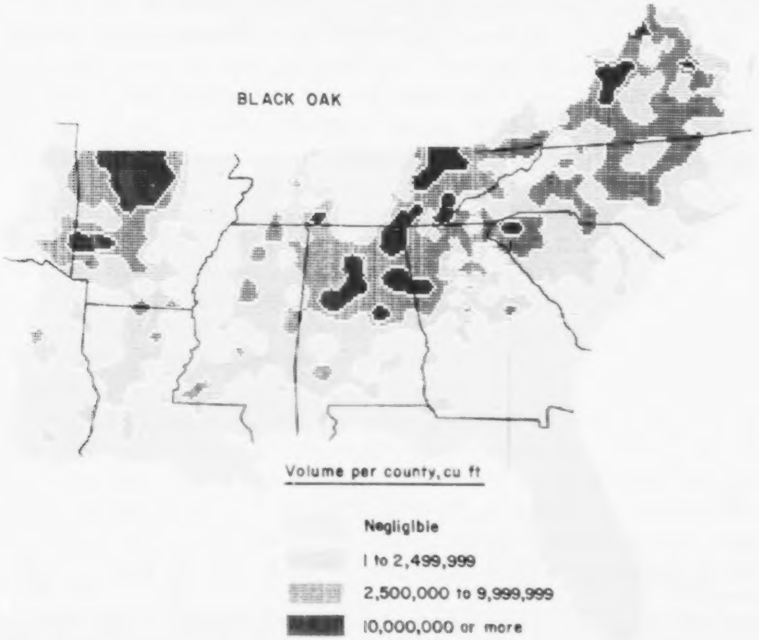

Figure 3-13.—SYMAP computer map of distribution and concentrations of black oak (*Quercus velutina* Lam.) on pine sites. (Drawing after Christopher et al. 1976.)

undamaged acorns are usually about 90 percent viable, but may be scarce because insects damage as much as two-thirds of the crop in years of poor production.

A mineral soil seedbed with a light winter covering of leaves favors black oak acorn germination. Vigorous early development of the primary root usually helps the seedling withstand drought.

Height growth of black oak begins early in the spring, about the time the leaves appear. In Missouri, 90 percent of all height growth of reproduction-sized trees took place within 11 days, and total height growth was essentially complete in 20 days or less. Diameter growth begins about April, peaks in June, and tapers off through July and August (Buchanan et al. 1962). Drought during these months slows diameter growth.

The stumps of small trees sprout freely after cutting or after the tops are killed back to the ground by fire. More than two-thirds of the black oak reproduction studied in the Missouri Ozarks was of sprout origin.

On the best sites, black oak may reach 150 feet in height and 4 feet in diameter, but most mature trees are from 60 to 80 feet tall and 2 to 3 feet in diameter. Black oak is a relatively short-lived tree, becoming physiologically mature at 100 years, with some individuals living 150 to 200 years. On most sites black oak seldom yields more than 250 board feet per tree at maturity. In West Virginia dominant black oaks grew about 90 pecent as fast as similar red oaks but surpassed scarlet oak, chestnut oak, and white oak.

Carmean (1971a) found that in the Central States black and scarlet oaks grow more rapidly than white oak for the first 50 or 60 years, but at 100 years white oak will be the tallest oak in the stand. His data relating black oak tree height to age and site index (tree height in feet at age 50) follow:

	Tree height at 3 ages		
Site index	20 years	80 years	100 years
Feet		*Feet*	
30	13	42	47
50	24	64	72
70	37	87	93
90	50	107	112

Fully-stocked oak stands, in which black oak is a component, may contain from 2,000 to 12,000 board feet per acre. Growth rates of managed stands vary from 150 to 350 or more board feet per acre per year, with a rotation age of 90 to 100 years for sawlog production. Fully-stocked 100-year-old stands yield 7,750 board feet (Scribner Scale) per acre on average-quality sites, and nearly 20,000 board feet per acre for good sites. On below-average sites, where black oak commonly occurs, volume may be as low as 3,350 board feet per acre at maturity.

On southern pine sites, growth is very slow. A sample of ten black oak trees (5.5 to 6.5 inches in dbh) collected from pine sites throughout the species' southern range averaged 39 years of age, 6 inches in dbh, and 49 feet in height (table 3-1).

Black oak is intermediate in shade tolerance. Seedlings usually die soon after being overtopped, but sprouts may persist longer. Black oak is more tolerant than yellow-poplar and less tolerant than white oak, hickory, elm, and blackgum. Because of its intolerance, black oak only persists in a mixed stand when its crown is in the upper canopy.

The boles of black oaks are relatively free of branches in dense stands; but in understocked stands, large branches may persist for many years, even though dead. Artificial pruning or partial cutting in well-stocked stands sometimes stimulates sprouting of dormant buds on the bole. There is evidence, however, that dominant trees are less likely to produce sprouts than trees in the other crown classes.

Together with other oaks and hickory, black oak is a component of the climax forest in the central and southern hardwood regions. Unlike a true climax tree, however, black oak rarely succeeds itself unless some major disturbance occurs in the forest canopy. On the poorest-quality sites, black oak may be replaced by post or blackjack oaks in the West, and by chestnut and scarlet oaks in the East and South.

Trees up to pole-timber size are easily killed back to the ground by fire, and trees of all ages and sizes are damaged severely by ground fires. Although fires seldom kill the larger trees, they cause fire scars that admit insects and disease. Heart rot initiated in fire scars, branch stubs, and other wounds is the chief defect in black oak; in parts of the Missouri Ozarks a third of the volume has been considered worthless because of this defect.

OAK, BLACKJACK (*Quercus marilandica* Muenchh.)

Blackjack oak grows throughout the South except in peninsular Florida and the Mississippi Delta. Its range extends to west-central Texas and Oklahoma, but north only to New Jersey and southern Iowa (fig. 3-14).

Because blackjack oak is considered non-commercial, no description of it appears in *Silvics of forest trees of the United States* (U.S. Department of Agriculture, Forest Service 1965), nor is survey data on its volume distribution available.

The tree is common on some pine sites, is a prolific sprouter, grows slowly, has a short bole, and is difficult to deaden. For these reasons blackjack oak infests important acreages within its range and inhibits growth of faster growing trees. For example, it has been estimated that most stands within the 15 million acres of Missouri's forest land contain blackjack oak and that in 1953 only one out of every three of these trees had then, or ever would have, commercial value (Clark and Liming 1953).

On southern pine sites, height as well as diameter growth is very slow. A sample of 10 blackjack oak trees (5.6 to 6.4 inches in dbh) collected from pine sites throughout the species' southern range averaged 39 years of age, 6 inches in dbh, and only 33 feet in height (table 3-1).

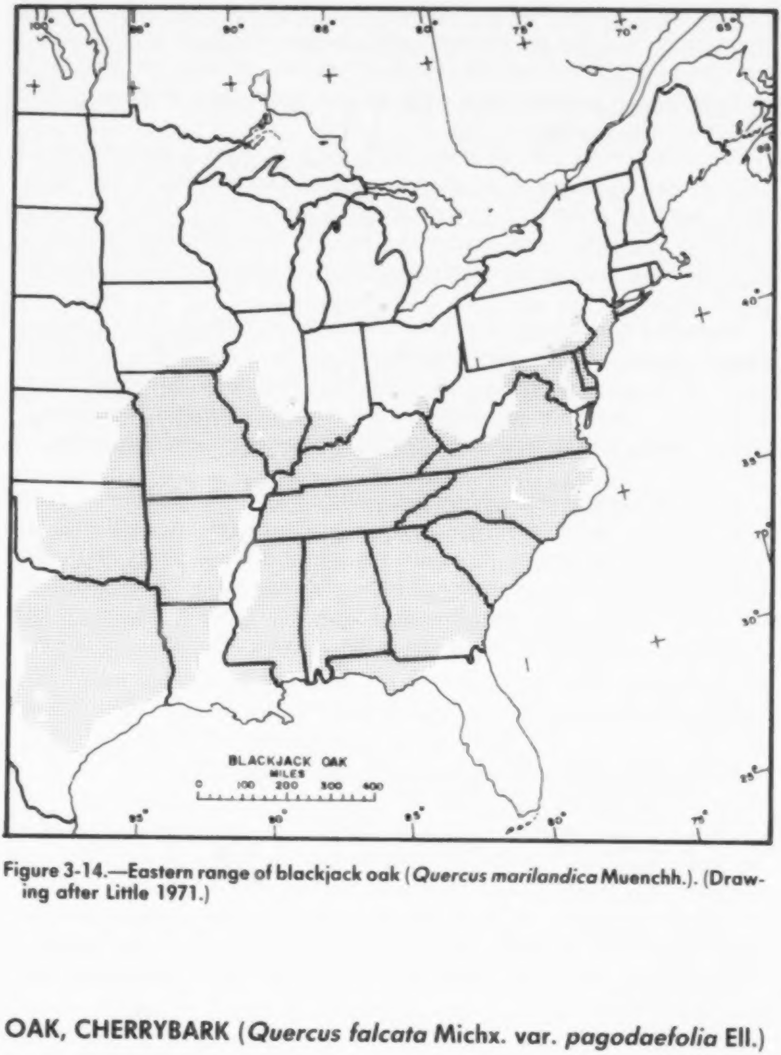

Figure 3-14.—Eastern range of blackjack oak (*Quercus marilandica* Muenchh.). (Drawing after Little 1971.)

OAK, CHERRYBARK (*Quercus falcata* Michx. var. *pagodaefolia* Ell.)

Cherrybark oak is a southern tree, growing mainly in the Coastal Plain from Maryland to eastern Texas. In Florida it is found only west of the Appilachicola River. Its range extends up the Mississippi to the mouth of the Ohio.

The tree is widely distributed on the best sites in first bottoms and on well-drained terrace and colluvial sites along both large and small streams. It develops best on a loamy well-drained soil. Although uncommon on clay soils, it is generally of good form and quality on such soils if the drainage is good but very inferior where drainage is poor. It is a lowland tree but seldom is numerous on wet or swampy soils.

Cherrybark oak also grows on Coastal Plain upland sites. It occurs on hammocks which are localized areas not necessarily associated with any stream but usually well-drained and with a deep soil of good texture. It grows well on loessial soil such as the Brown Loam Bluffs bordering the eastern edge of the Mississippi River alluvial plain from Louisiana north. Other favorable sites occur in the rolling hills of the lower Piedmont and upper Coastal Plain. Here the species grows well in branch heads, coves, and slopes with deep surface soils.

About 45 percent of total cherrybark oak volume in the South occurs on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations are greatest in counties of west-central Louisiana, southern Arkansas, and southwestern Mississippi (fig. 3-15). Total pine-site volumes are greatest in Mississippi, Louisiana, and Arkansas (120, 110, and 109 million cubic feet, respectively). North Carolina, Alabama, South Carolina, and Texas have pine-site volumes of 40, 43, 52, and 69 million cubic feet. Tennessee, Georgia, and Virginia have volumes of 6, 12, and 17 million cubic feet. Oklahoma has only 1 million cubic feet, and in Florida no cherrybark oak is reported on pine sites.

Cherrybark oak flowers appear with the leaves in March and April. The acorn, borne solitary or in pairs, is hemispherical or nearly globular, ½ inch long, and averages about 750 per pound. The seeds ripen and fall during September to November of the second year, and typically germinate the following spring.

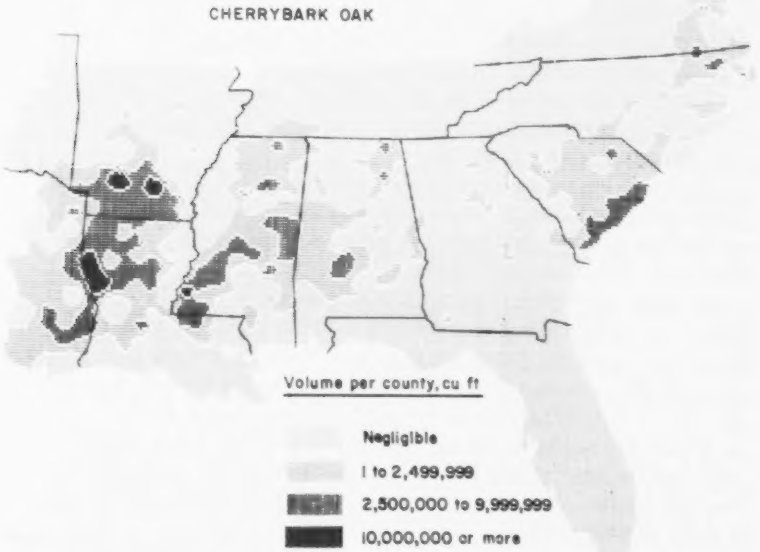

Figure 3-15.—SYMAP computer map of distribution and concentrations of cherrybark oak (*Quercus falcata* Michx. var. *pagodaefolia* Ell.) on pine sites. (Drawing after Christopher et al. 1976.)

Submersion in water for 34 days impaired germination. Acorn collections at the Santee Experimental Forest in South Carolina showed that insect-damaged acorns are readily distinguished from sound ones by the color of the cup scar; good acorns have a light, almost lemon color, while defective acorns are dull brown.

Seedbearing begins when the trees are about 25 years old, and optimum production is reached when they are between 50 and 75 years of age. Good crops are frequent, usually at 2-year intervals, with light crops in intervening years. A freeze in April 1955, after the flower buds opened, resulted in a complete crop failure over much of the tree's range in 1956. Dissemination largely depends on hoarding activity of animals, especially squirrels. Gravity is a minor means of dissemination on the steeper terrace margins.

The domestic hog, which ranges in large numbers over the bottom lands of the South, probably consumes a major part of the annual crop of cherrybark oak acorns. Within the range of this oak, animals and birds include acorns as a substantial part (10 percent or more) of their diets. Among these the heaviest eaters are the gray squirrel, wild turkey, and the blue jay, followed by the wood duck, red-bellied woodpecker, red-headed woodpecker, white-breasted nuthatch, common grackle, raccoon, white-tailed deer, and the eastern fox squirrel.

Cherrybark oak regenerates naturally on areas protected from fire and grazing. Being intolerant, it requires full light for development, which in turn induces heavy competition from annual weeds, vines, briars, and brush. It often makes its best development in old fields on well-drained loamy soils.

Studies in progress at the Santee Experimental Forest, S.C., show a third-year survival of 82 percent for planted 1-0 nursery stock, and 30 percent for direct-seeded acorns, on sandy loam soils associated with the first and second bottoms of small coastal streams.

Cherrybark oak sprouts from the stump but sprouting is not a dependable means for obtaining desirable natural regeneration. Like most oaks, this tree is difficult to propagate by cuttings.

Cherrybark oaks often attain heights and diameters of 100 to 130 feet and 3 to 5 feet, respectively, which classes them with the largest of the southern red oaks. It is one of the hardiest and fastest growing oaks, and it grows well on more sites than most bottom land oak species.

On bottom land sites, diameter growth rates range from 3 to 6 inches in 10 years. On southern pine sites, however, diameter growth of small trees may be less than 2 inches in 10 years. A sample of 10 cherrybark oak trees (5.6 to 6.3 inches in dbh) collected from pine sites throughout the species' range averaged 32 years of age, 6.0 inches in dbh, and 47 feet in height (table 3-1).

Volume and yield data are not available for this tree, which usually grows as individuals or small groups in mixed stands. Occasionally, with Shumard oak, it dominates a stand. It cannot live under shade and is usually found in a dominant or codominant position.

Because of its good form and quality, cherrybark oak is regarded as one of the best red oaks. Following release or injury, this oak produces sprouts but to no greater degree than many other oaks.

On poorly drained clay flats or other poor sites, mature trees are often infested with borers or the wood is mineral streaked. Borer damage, often fire related, is common in overmature and fire-scarred trees. Mineral streaks appear to follow wind damage.

OAK, CHESTNUT (*Quercus prinus* L.)

Until 1900, most chestnut oak was cut mainly for its bark, from which tannin was extracted. At the present time, however, it is much more valuable as a source of lumber and veneer. Although important in the white oak lumber trade, its lack of tyloses prohibits its use for tight cooperage.

Chestnut oak in the South grows mainly in the Highland Region of Virginia, the Carolinas, Georgia, Alabama, and Tennessee. Its main range extends north parallel to the Appalachians to Ontario and New England. It reaches maximum size and quality on mountain slopes in the Carolinas and Tennessee.

Chestnut oak it typically an upland, dry-site species. It grows better than most other oaks on dry, sandy, or gravelly soils, although it reaches maximum size in well-drained coves and bottom sites. The soils on which it grows vary from the gray-brown podzolic in the North to the red and yellow podzolic in the South. It reaches elevations of about 4,500 feet in the Appalachians.

About 31 percent of total chestnut oak volume in the South is found on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations are greatest in counties of northern Alabama, northern Georgia, western Tennessee, eastern North Carolina, and in the western half of Virginia (fig. 3-16). Total pine-site volumes of chestnut oak are greatest in Virginia and Tennessee, which have 685 and 571 million cubic feet. Georgia, Alabama, and North Carolina have pine-site volumes of 224, 284, and 300 million cubic feet. South Carolina has 35 million cubic feet while Mississippi has only 3 million cubic feet. Southern States with no pine-site volume of chestnut oak are Arkansas, Florida, Louisiana, Oklahoma, and Texas.

Chestnut oak flowers in early April in the Southern Appalachians. Heavy flowering does not necessarily indicate there will be heavy fruiting because freezing temperatures may reduce acorn production. Chestnut oak acorns mature in 1 year and drop before those of other oaks. For the Southern Appalachians, good seed crops are predicted once in 4 to 7 years; other reports predict good crops as often as twice in a 5-year period. Acorn production increased with tree size up to diameters of 26 inches; moreover, the percentage of sound acorns increased as crop size increased. The chestnut oak acorn is a favorite food of white-tailed deer and gray squirrel, and of larger birds such as the turkey. Chestnut oak acorns germinate soon after falling if seedbed conditions are favorable. In a Central States study, minimum litter depth of 1 inch and a maximum of 2 inches with some shade on the seedbed appeared most favorable.

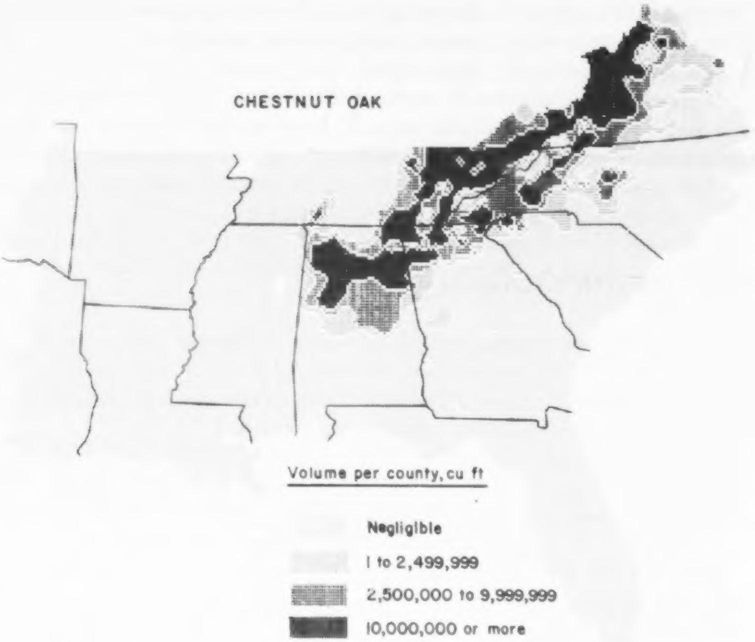

Figure 3-16.—SYMAP computer map of distribution and concentrations of chestnut oak (*Quercus prinus* L.) on pine sites. (Drawing after Christopher et al. 1976.)

Chestnut oak is regarded as a prolific and persistent sprouter; it has been estimated that 75 percent of its reproduction in the Southern Appalachians is of sprout origin. As with other oaks, however, sprouting vigor decreases as the size and age of the stump increases, and decay is most prevalent in sprouts from large stumps.

Chestnut oak is a medium-size tree normally maturing at 60- to 80-foot heights and 20- to 30-inch diameters, depending on site quality. Maximum size is a height of 100 feet and a diameter of 6 feet.

As with most of the white oaks, growth is slow. In West Virginia, the site index ratio of chestnut oak was 0.98, and for white oak it was 0.95 compared with 1.00 for northern red oak on the same site. In the Southern Appalachians chestnut oak grew faster than American beech (*Fagus grandifolia* Ehrh.), the hickories, and yellow birch (*Betula alleghaniensis* Britton), but slower than the red oaks, American ash, red maple, or sugar maple. In Pennsylvania, chestnut oak made slower diameter growth than red, black, scarlet, or white oaks.

Carmean (1971a) found that in the Central States chestnut oak was intermediate in height growth between white oak and black and scarlet oaks. White oak was tallest at age 100, but black and scarlet oaks grew more rapidly than white oak during the first 50 to 60 years. Carmean's data relating chestnut oak tree height to age and site index (tree height in feet at age 50) are abstracted as follows:

	Tree height at 3 ages		
Site index	20 years	80 years	100 years
Feet		- - - - - *Feet* - - - - -	
30	17	40	44
50	27	67	73
70	37	89	97
90	47	113	122

Sawtimber yield from chestnut oak stands on dry slopes and ridges of the Southern Appalachians is about 7,000 board feet per acre at 80 years. Annual growth is about 90 board feet per acre per year during the 10-year period between 70 and 80 years of age. Periodic growth on average sites is maximum, about 100 board feet per acre per year, when the trees are about 100 years old. Average cordwood yield at 100 years is etimated to be 38 cords per acre, and the periodic growth rate is about one-half cord per acre per year.

In the Mountain Region of western North Carolina chestnut oak contributes one-eighth of the total volume of all sawtimber—more than any other tree. Economic maturity of the species on average to good sites, based on lumber values and rates, is reached when the trees are from 21 to 25 inches dbh; the larger diameter is for trees on good sites and those with good vigor. On poor sites the tree rarely attains these diameters.

Chestnut oak is intermediate in tolerance. In forest stands its bole is usually relatively clear of branches, and on good sites it has excellent form. Reproduction tends to persist even under overhead shade although, like many other oaks, the tops will die back and resprout repeatedly unless they are released to provide full light.

Chestnut oak is the most resistant of the oaks to heart and sapwood decay fungi. However, because it commonly grows on dry ridges and exposed sites where fires burn intensely, it frequently has a defective bole.

OAK, LAUREL (*Quercus laurifolia* Michx.)

Laurel oak is found in the Southern Coastal Plain from southeastern Virginia to southern Florida and southern Texas. The best formed trees are found in greatest abundance in north Florida and Georgia. In its principal range it has been considered one of the least valuable red oaks, only occasionally cut for pulpwood and rarely used for crossties and timbers (McKnight 1958).

Laurel oak usually occupies a well-drained sandy soil with good water-supplying capacity. It is frequently found in sandy soil along the edges of rivers and swamps as well as in rainwater flats that are only rarely inundated. In central Florida it can be found in mesic hammocks, and in west Florida in the sandy hills adjacent to swamps. It occasionally invades the edges of sandy ridges.

About 29 percent of total laurel oak volume is found on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations are greatest in counties of southeast Alabama, northern Florida, eastern Georgia, and the eastern coast of South Carolina (fig. 3-17). Total pine-site volume of laurel oak is greatest in Georgia, which has 254 million cubic feet. Alabama, South Carolina, and Florida have pine-site volumes of 95, 113, and 146 million cubic feet. Virginia, Mississippi, Texas, and Louisiana have 3, 12, 18, and 42 million cubic feet, respectively. Arkansas, Mississippi, Oklahoma, and Tennessee have no appreciable volume of laurel oak on pine sites.

Flowering and pollination take place in February and March at about the time the last of the previous year's leaves are shed. Flower crops are usually good every year, but hard rains may interfere with pollination.

Seed production starts when trees are 15 to 20 years old and soon afterward becomes very prolific. Acorns require 2 years to mature, and fall to the ground in late September and October. There are about 600 sound acorns (without cup) to a pound. Dissemination is mainly by squirrels, but is aided by gravity and runoff during rains. No information is at hand on seedling development.

When cut or burned, young laurel oaks produce many sprouts from the base of the stump. Older trees do not sprout vigorously and their sprouts are more susceptible to decay than those of young trees.

Laurel oak grows rapidly on good sites and is usually mature in about 50 years. Its rapid juvenile growth is one reason why it has been widely used as an ornamental. Trees with diameters at breast height of 3 or 4 feet and heights of 100 feet occur, but they are rare.

On southern pine sites, growth is slower. A sample of 10 laurel oak trees (5.6 to 6.3 inches in dbh) collected from pine sites throughout the species' range averaged 33 years of age, 6.0 inches in dbh, and 48 feet in height (table 3-1).

Laurel oak often becomes established and grows up through the dense canopy of a swamp border. Natural pruning is poor and large limbs persist on the bole many years, even under a dense canopy.

Fire is a serious hazard to this species. The thin bark is killed by light ground fires. Heart rots are very common in trees subject even to occasional burns.

OAK, NORTHERN RED (*Quercus rubra* L.)

A widely distributed tree of Eastern United States, northern red oak is common in the parts of the South lying north of the Coastal Plain, including the mountains of Arkansas and Oklahoma. Its range extends south in Georgia and Alabama to near the Florida boundary; outlying parts of the range are in Mississippi and Louisiana. Northward, its range extends well into Canada.

Northern red oak grows in soils ranging from clay to loamy sands, and from deep, stone-free to shallow, rocky soils. It is most frequent on northerly or easterly aspects, lower and middle slopes, coves and ravines, and valley floors. Best sites have fine-textured soil, and a high water table. Normally, northern red oak is a component of subclimax to climax forest cover types, and pure stands are rare.

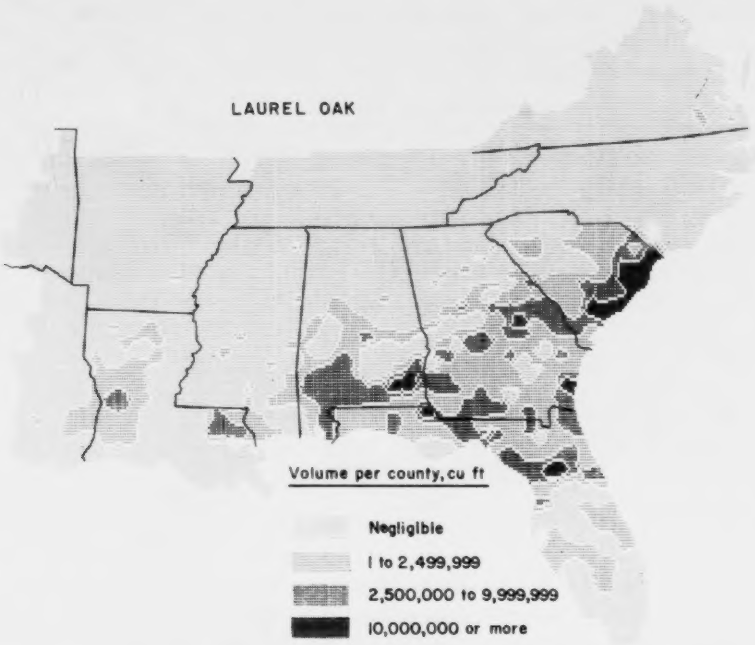

Figure 3-17.—SYMAP computer map of distribution and concentrations of laurel oak (*Quercus laurifolia* Michx.) on pine sites. (Drawing after Christopher et al. 1976.)

About 38 percent of total northern red oak volume growing in the 12 Southern States is found on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations are greatest in counties of northwest Arkansas, eastern Tennessee, and central Virginia (fig. 3-18). Total pine-site volumes of red oak are greatest in Virginia, Arkansas and Tennessee (264, 221, and 208 million cubic feet, respectively). North Carolina and Georgia each have pine-site volumes of about 150 million cubic feet, while Alabama has 105 million cubic feet. Mississippi, Oklahoma, and South Carolina have pine-site volumes of 6, 12, and 55 million cubic feet. No appreciable pine-site volumes of northern red oak were found in surveys of Florida, Louisiana, and Texas.

Both male and female flowers of northern red oak develop before or with the leaves in April and May. The male flowers are borne in catkins in the axils of the previous year's leaves. The female flowers are solitary or occur in two- to many-flowered spikes in the axils of the current year's leaves.

The acorn of northern red oak matures in 2 years and ripens in September and October. The tree begins to fruit when 25 years old, but abundant acorn production begins about age 50. Good seed crops are produced every 2 to 5 years. Acorns of this tree are an important food for rodents, squirrels, deer, and turkey; because so many are destroyed by these animals and by insects, seedling regeneration is adequate only in years of high acorn production.

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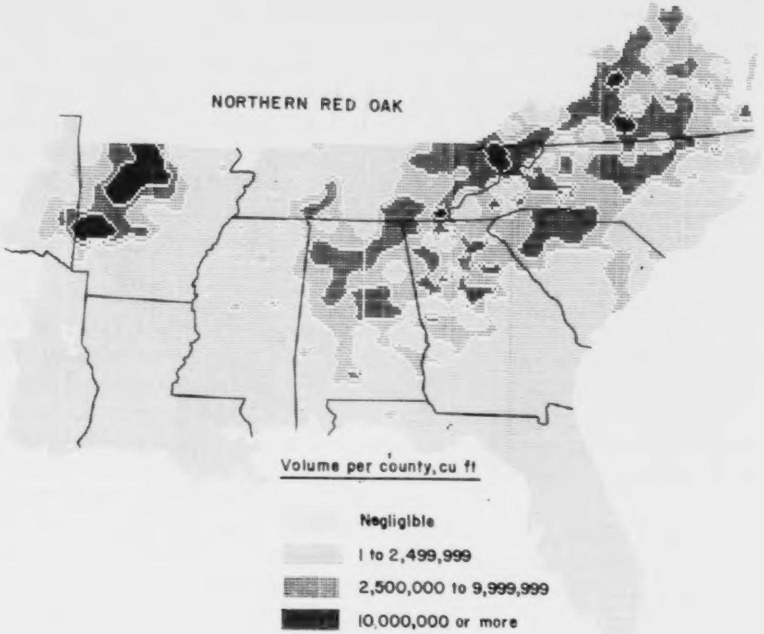

Figure 3-18.—SYMAP computer map of distribution and concentrations of northern red oak (*Quercus rubra* L.) on pine sites. (Drawing after Christopher et al. 1976.)

The acorns of northern red oak germinate the spring after seed fall, after dormancy has been broken by overwintering in the litter. They germinate best in soil covered by a layer of leaf litter. Available moisture is critical to early survival and growth of northern red oak seedlings. Prompt penetration of the soil by the rapid-growing taproot permits seedlings to withstand much dryness while still very small.

Young northern red oaks sprout vigorously and prolifically when cut or killed by fire; sprouts may form on red oak stumps as large as 22 inches in diameter. In a Connecticut survey 81 percent of the red oak stumps examined had sprouted. While more small stumps than large stumps sprout, the large stumps yield more stems; by age 23, however, sprouts in Midwest red oaks averaged about four stems per clump regardless of parent tree dbh (Johnson 1975).

Many second growth northern red oak stands are of seedling and stump sprout origin. Seedling sprouts develop about as well as seedlings. Stump sprouts, however, are prone to decay from the parent stump. Sprouts arising at or below ground level are least likely to decay.

Northern red oak usually grows to be 70 to 90 feet tall and 2 to 3 feet or more in diameter. On the west slope of the Alleghenies and in the Ohio River Valley it may attain a height of 160 feet and a diameter of 5 feet. Under forest conditions it develops a tall, straight, columnar bole and prunes itself well. Open-grown trees tend to have short boles and large spreading crowns.

In the Tennessee Valley, the 10-year rate of diameter growth was observed at 1.71 inches, and in North Carolina, it was 2.53 inches. On good sites (site index 70) in West Virginia and Maryland, the 10-year diameter growth average 1.56 inches.

On Southern pine sites, the growth rate is slower. A sample of 10 northern red oaks (5.5 to 6.3 inches in dbh) collected from pine sites throughout the species' southern range averaged 40 years of age, 5.9 inches in dbh, and 52 feet in height (table 3-1).

A study in the Boston Mountains of Arkansas of species of the red oak group—of which northern red oak is an important component—showed height growth related to tree age and site index (tree height at age 50) as follows (Graney and Bower 1971):

	Tree height at 2 ages	
Site index	20 years	100 years
Feet	- - - - - *Feet* - - - - -	
40	20	45
50	24	61
60	30	80
70	33	100
80	38	120

Northern red oak tolerance is intermediate. The species is less tolerant than eastern hemlock (*Tsuga canadensis* (L.) Carr.), sugar maple, American beech, basswood (*Tilia americana* L.), and the hickories, but more tolerant than the ashes, yellow-poplar, and black cherry (*Prunus serotina* Ehrh.). Among the oaks, it appears to be less tolerant than white oak but more tolerant than black and scarlet oak. Under severe competition from shrubs and herbs, 81 percent of the red oak reproduction that followed clear cutting failed in 5 years. Only 36 percent was lost under light or medium competition.

Northern red oak responds well to release. Old growth trees develop few epicormic branches, but such branching may occur on second growth trees.

Although fire will rarely kill pole- and sawtimber-size trees, fire injury to northern red oak is usually followed by decay.

OAK, POST (*Quercus stellata* Wangenh.)

Post oak occurs in all the South except lower Florida and the Mississippi Delta. Its range extends north to southeast Iowa and southern New England, and west to the Texas Panhandle. Inclined to be shrubby in the North, post oak is a larger tree and more numerous in the southern Coastal Plain, the Piedmont, and the lower slopes of the Appalachians. It is a common tree in the Southwest and grows in pure stands known as the **Cross Timbers** in the prairie transition region of central Oklahoma and Texas. With blackjack oak and hickories, it forms the western outposts of the eastern deciduous forests in the Southern Plains.

Post oak grows in a wide variety of soils and on many sites. It is found in Podzols, Gray-Brown Podzolics, Red and Yellow Soils, and Southern Chernozems varying in reaction from strongly acid to neutral or slightly alkaline. It commonly grows on gravelly or sandy upland soils of low organic content. Typical sites are rocky ridges, sandy outcroppings, and southern exposures. It is also a characteristic tree of sites that are alternately waterlogged and hard and dry, such as the Alabama and Mississippi flatwoods.

Delta post oak (*Q. stellata* var. *mississippiensis* (Ashe) Little) occurs on the lower Mississippi River Valley bottom lands, principally on second bottoms, but also on low ridges and high flats. It grows best on heavy loamy soils that have abundant moisture and, perhaps, slow but not poor drainage. It is not important on pine sites.

About 74 percent of total post oak volume in the South is on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations are greatest in counties in Oklahoma, Texas, Arkansas, Louisiana, Mississippi, Alabama, and North Carolina (fig. 3-19). Total pine-site volume of post oak is greatest in Arkansas (801 million cubic feet) followed by Mississippi, Texas, Alabama and Louisiana (453, 405, 381 and 307 million cubic feet, respectively). Next greatest pine-site volumes are in North Carolina, Georgia, Oklahoma, Tennessee, and South Carolina (261, 252, 226, 139, and 132 million cubic feet). Virginia has 72 million cubic feet and Florida only 15 million cubic feet of post oak growing on southern pine sites.

Flowers appear on post oak when the leaves are about a third grown. Flowering begins during March in Texas and extends through May further north. The acorns mature in one growing season and fall soon after ripening—from September to November. In the Southwest, peak seedfall is in mid-October. Late freezes, after the start of flowering and leafing, infrequently cause seed crop failures.

In common with many other oaks, post oak begins to bear acorns when it is about 25 years old. Good crops are produced at 2- to 3-year intervals, although at several locations in Missouri over a 6-year period, post oak consistently averaged only 200 seeds per tree per year while white, blackjack, black, and scarlet oaks of the same size and on the same sites bore from 500 to 2,400 acorns per tree. Isolated trees in open fields in east Texas consistently produced well. Elsewhere in Texas, trees under 6 inches dbh had no acorns, but in west-central Louisiana trees as small as 4.6 inches dbh produced well. In the latter case, mast production from 1950 through 1952 apparently was not affected by stand density nor did it differ among trees on different soil types. Best yields are from large dominant and codominant trees, but the maximum recorded annual yield, 1,495 acorns, came from a tree only 8.6 inches dbh.

Post oak acorns, disseminated chiefly by gravity and by animals, average 400 per pound but may range from 240 to 635. They are heavily attacked by insects (chiefly by weevils, *Curulio* spp.) and many are eaten by birds and rodents. In a study in Missouri from 1947 through 1952, half of the nuts collected in traps were immature and over 80 percent were wormy.

The best seedbed for post oak is a moist soil covered with an inch or more of leaf litter. Acorns germinate in the autumn soon after they drop. Seedlings have especially thick taproots, usually thicker than the shoot, but overall root devel-

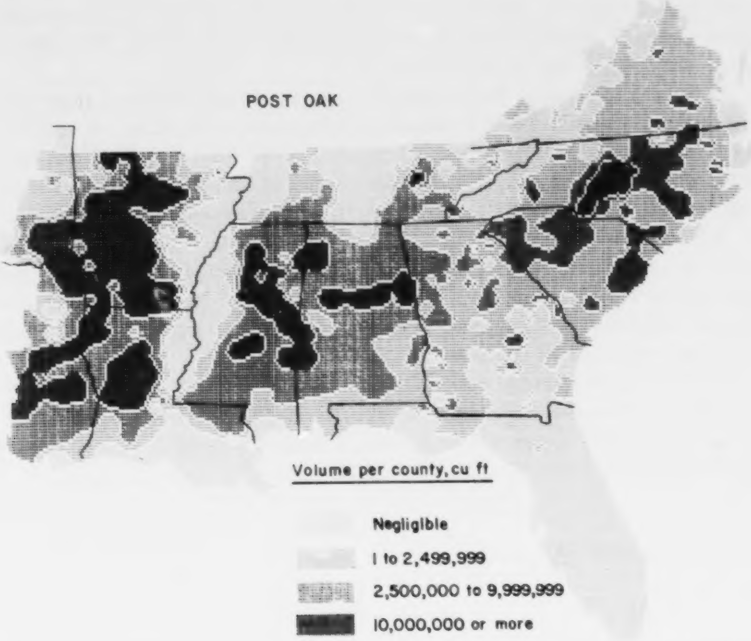

Figure 3-19.—SYMAP computer map of distribution and concentrations of post oak (*Quercus stellata* Wangenh.) on pine sites. (Drawing after Christopher et al. 1976.)

opment is significantly less than that of northern red, scarlet, white and blackjack oaks.

Post oaks up to 8 and 10 inches in diameter sprout prolifically after being cut or burned. Along the southwestern margins of its range, post oak spread rapidly into former grasslands after periodic prairie fires were controlled. Much of this extension was undoubtedly of sprout origin. In one study in which potted seedlings were deprived of moisture until the above-ground parts died, two to three times as many post oaks sprouted after normal moisture was restored than did white, blackjack, northern red, and scarlet oaks. In another study, post oak had more one-stem clumps and fewer sprouts per clump than did black oak, chestnut oak, white oak, or scarlet oak. This characteristic would be important in culture by coppice except that post oak grows more slowly than the others.

In the Southeast, mature post oaks are from 50 to 60 feet tall and from 12 to 24 inches dbh. Maximum height rarely exceeds 100 feet and diameters exceeding 48 inches are uncommon. In the extreme western part of its range, mature trees are seldom larger than 30 to 40 feet tall and 15 to 18 inches dbh. Height and diameter growth are usually slower for post oak than for any of the associated trees except blackjack oak. Ten-year diameter growth generally averages less than 2 inches, and in central Oklahoma it may be only ½ inch. On southern pine sites in general, diameter growth is somewhat faster, but still very slow; a sample of 10 post oak trees (5.7 to 6.2 inches in dbh) collected from pine sites throughout the species' southern range averaged 51 years of age, 6.0 inches in dbh, and only 39 feet in height (table 3-1).

In Robertson County, Texas, diameter growth of individual post oaks (trees averaging 6.8 inches dbh) was stimulated when most of the stand was removed to favor forage production. Post oak stands thinned from 65 square feet basal area per acre to 13 square feet grew twice as fast in diameter as the uncut check plots (0.14 inch compared to 0.07 inch) in the two ensuing growing seasons.

Average post oak stands in east Texas contain a volume of about 7½ cords per acre. In an Oklahoma woodland, typical of the dry upland post oak type, post oaks 12 inches dbh and larger made up 64 percent of the sawtimber volume (Doyle rule) in a stand averaging nearly 2,000 board feet per acre. The average post oak contained 70 board feet.

Post oak is intolerant of competition and shade. Because of its slow height growth it is often overtopped by other trees, including most other oaks. However, post oak tends to persist and become dominant on poor sites because it is more drought resistant than many of its associates.

OAK, SCARLET (*Quercus coccinea* Muenchh.)

Scarlet oak, so named because of the brilliant scarlet color of its autumn leaves, is common in the Highland Region of the South east of the Mississippi River and in scattered locations in the Coastal Plain. Its range extends into southeast Missouri and northeast into New England. It is frequently and successfully planted outside its natural range as an ornamental tree.

Scarlet oak is found on a wide variety of soils, including the Gray-Brown Podzolic Soils of the North and the Red and Yellow Podzolic Soils of the South. It is commonly found on average to poorer than average sites and is a typical upland oak on ridges and upper and middle slopes.

In the Southern Appalachians, the site index of scarlet oak is from 37 to 91 feet (at 50 years). This tree has the highest site index ratio of the five common oaks found in the Northern Appalachians. Although it apparently regenerates and competes best on the poorer and lighter soils, its site index increases with increasing depth of A horizon, decreasing amounts of sand in the A horizon, and with lower positions on the slope. In the Appalachians, position on the slope along with aspect, grade of slope, and depth of soil to bedrock are important site quality factors, too.

About 62 percent of total scarlet oak volume in the South is on southern pine sites (tables 2-7 through 2-18). Pine site concentrations are greatest in counties of northern Alabama, northwestern South Carolina, east Tennessee, west-central North Carolina, and west-central Virginia (fig. 3-20). Virginia has the greatest volume of scarlet oak growing on pine sites (510 million cubic feet) followed by North Carolina with 420 million cubic feet. Tennessee, Georgia, and Alabama have pine-site volumes of 321, 247, and 166 million cubic feet, respectively. States with lesser pine-site volumes are South Carolina, Mississip-

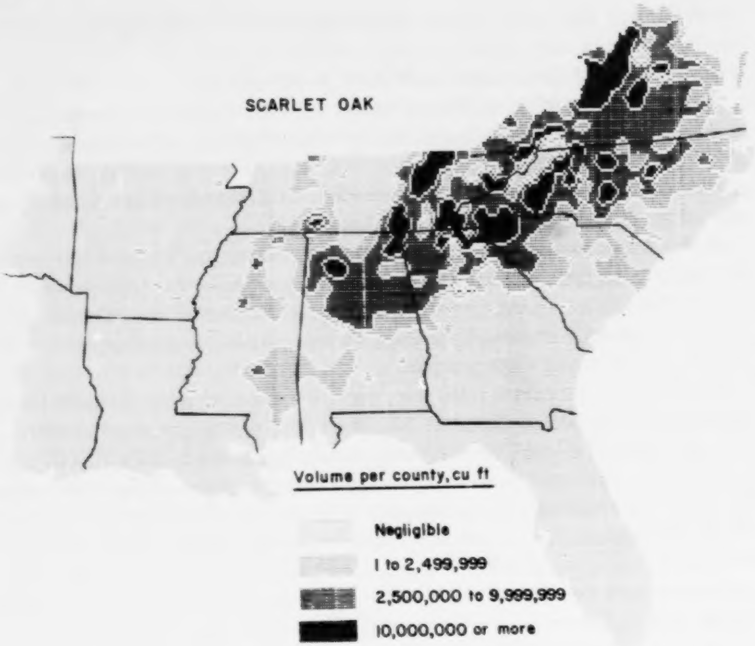

Figure 3-20.—SYMAP computer map of distribution and concentrations of scarlet oak (*Quercus coccinea* Muenchh.) on pine sites. (Drawing after Christopher et al. 1976.)

pi, and Arkansas (94, 39, and 2 million cubic feet, respectively). No pine-site volume of scarlet oak is reported in Florida, Louisiana, Oklahoma, or Texas.

Scarlet oak flowers in April or May, depending on latitude, elevation, and variations in weather. Two growing seasons are required for the acorns to mature. Good scarlet oak seed crops have been observed every 3 or 4 years in the Southern Appalachians, but generally good crops of seed occur irregularly. In a Missouri study, crops of scarlet oak acorns were more variable than those of black, white, post, and blackjack oaks, but scarlet oak was the most prolific seeder in good seed crop years.

In the Southern Appalachians, scarlet oak seed production increased rapidly with tree size up to a diameter of 20 inches and then leveled off. In the Missouri study, seed production was independent of measured tree characteristics. Of five oaks studied in the Southern Appalachians, scarlet oak was the last to drop its acorns in the fall. From 20 to 60 percent of the scarlet oak acorns were sound, and the proportion of sound acorns was highest in years of greatest seed production.

Scarlet oak acorns are a choice food for eastern gray squirrels, chipmunks, mice, and birds, especially the blue jay. In a Southern Appalachian study, 44 percent of acorn loss was attributed to birds and squirrels before the acorns fell;

insect damage after acorn fall was responsible for the remaining 56 percent. A similar degree of insect damage was reported in Missouri; after seedfall, insects did 64 percent of the damage, and birds 36 percent.

A light covering of forest litter is helpful to germination of scarlet oak acorns; no litter, and deep litter are less favorable. Partial cutting provides more favorable conditions for acorn germination than does seed-tree cutting. A two-cut shelterwood method has been recommended, the first to favor germination, the second to release the established seedlings.

In the Appalachians, scarlet oak stumps sprout when older and larger than stumps of other oaks. Of scarlet oak sprouts examined in the Appalachians, 28 percent had butt rot; sprouts from large stumps were more subject ot butt rot than sprouts from small stumps. Spreading rot may weaken trees to a point where they break off during high winds.

Scarlet oak is a medium-sized tree, normally maturing when 60 to 80 feet in height and 2 to 3 feet in diameter. Maximum size is a height of about 100 feet and a diameter of 4 feet. The tree grows rapidly and matures early. In a Georgia study, scarlet oak ranked next to yellow-poplar in rate of diameter growth, but in another study northern red oak outgrew both scarlet oak and yellow-poplar.

On poor sites, scarlet oak probably grows faster than most of its associates. A sample of 10 scarlet oak trees (5.6 to 6.4 inches in diameter) collectd from pine sites throughout the species' southern range averaged 33 years of age, 5.8 inches in dbh and 46 feet in height (table 3-1).

In a study of 559 dominant and codominant oaks sampled from Kentucky west to Missouri, Carmean (1971a) found that scarlet and black oaks grow more rapidly than white oak for the first 50 or 60 years; an abstract of his graphical data pertinent to scarlet oak follows (site index is expressed in feet of height at age 50):

	Tree height at 3 ages		
Site index	20 years	80 years	100 years
Feet		*Feet*	
40	21	51	54
60	30	78	84
80	39	101	108

Scarlet oak is one of the most intolerant of the oaks. It is rarely found in a suppressed or intermediate position in a stand, indicating that it cannot exist when it is overtopped. Almost always it is a dominant or codominant tree. It probably is able to maintain a position in the many forest types where it occurs because of its rapid growth rate and because it can withstand droughty conditions.

Because of its thin bark, scarlet oak is very susceptible to fire damage; if not killed outright, the tree is usually injured so that sap or heart rots enter. Additionally, heart rot may enter the bole through branch stubs, sometimes at an early age, and cause severe damage.

OAK, SHUMARD (*Quercus shumardii* Buckl.)

Shumard oak is found throughout the South except in the Appalachian mountains, peninsular Florida, and the Mississippi Delta. It occurs only locally in Virginia and parts of North Carolina. Its range extends north to southern Michigan.

In the Southern Forest Shumard oak grows on the well-drained soils of terraces, colluvial sites, and bluffs adjacent to large and small streams. It is also found in Coastal Plain hammocks but rarely on first-bottom sites. In central Texas and Oklahoma, the tree grows on dry, low limestone hills. In the southern part of the Central Forest, as well as in the Southern Forest and to the borders of the westen prairies, it also grows on dry uplands and ridges. Generally occurring as a single tree or in small groups, it never makes up more than a small part of the stand over a large area.

About 46 percent of total Shumard oak volume in the South is on southern pine sites (tables 2-7 through 2-18). Pine sites concentrations are nowhere heavy, but moderate concentrations (2.5 to 10 million cubic feet) are found in a few counties of Mississippi, Alabama, Georgia, and South Carolina (fig. 3-21). Total pine-site volume of Shumard oak is greatest in Mississippi (46 million cubic feet) followed by Alabama, Arkansas, and Georgia which have 25, 15, and 12 million cubic feet. Florida, Louisiana, Oklahoma, South Carolina, Tennessee, and Texas have from 1 to 6 million cubic feet of Shumard oak on pine sites; North Carolina and Virginia have no significant volume.

Flowering usually occurs in March or April. The acorn is borne singly or in pairs; it is oblong-ovoid and may be up to 1¼ inches long and 1 inch in diameter. Acorns ripen and fall in the second year, usually in November and December. Seed bearing begins when the tree is about 25 years old, and optimum production is reached when it is about 50. Good seed crops occur at intervals of 2 or 3 years with light crops in between, but sometimes the crop is lost by freezing. Acorn dissemination is largely dependent on animals, mainly squirrels. Along terrace margins and in the hilly sections of the tree's range, as in Texas and Oklahoma, gravity dissemination may be important. Acorns are frequently attacked by weevils; damaged ones display a dull brown cup scar on the nut, while a bright, light tan scar indicates a good acorn.

Because Shumard oak is intolerant, reproduction requires full light. Even so, it is puzzling that this tree which grows to such large size in the Coastal Plain and Delta regions, should be generally so uncommon and local in its distribution.

Shumard oak has not been widely seeded or planted. On sandy loam soils associated with small streams of the South Carolina Coastal Plain, survival of 1-0 nursery stock was 87 percent, of seedlings from directed-seeded acorns, 32 percent.

Like most southern oaks, Shumard oak probably sprouts best when young. It does not sprout prolifically on moist sites, as indicated by the absence of multiple stemmed trees in such locations. On dry sites, sprouting is more prolific. Like other oaks, Shumard is difficult to propagate by cuttings.

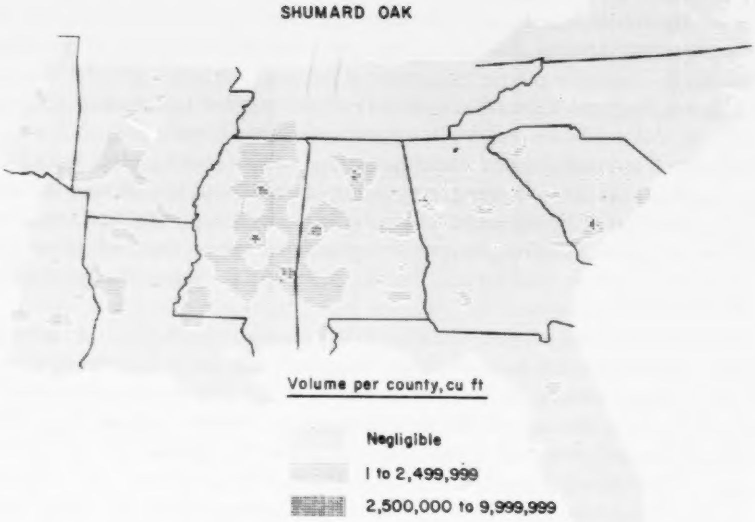

Figure 3-21.—SYMAP computer map of distribution and concentrations of Shumark oak (*Quercus shumardii* Buckl.) on pine sites. (Drawing after Christopher et al. 1976.)

Shumard oak is one of the largest southern oaks, developing a straight, tall clear trunk up to 4 or 5 feet in diameter and a total height of 90 to 125 feet on the best sites. Diameter growth in the Coastal Plain and Delta regions averages 3 to 4 inches in 10 years. On many southern pine sites, however, diameter growth may be only half this rapid. A sample of 10 Shumard oaks (5.5 to 6.5 inches in dbh) collected from pine sites throughout the species' southern range averaged 35 years of age, 6.1 inches in dbh, and 52 feet in height (table 3-1).

Because Shumard oak generally occurs singly or in very small groups, volume and yield values for the tree on an acre basis are not available. Pole stands containing Shumard oak will often have more than 175 trees per acre 5 to 11 inches in diameter breast high. In mixed old-growth stands that include this oak, volumes are as much as 30,000 board feet per acre.

On moist sites, exposure to sufficient sunlight to establish Shumard oak also induces a heavy growth of annual weeds, vines, briars, and brush. Release from such competition may be required to insure seedling survival and growth. Shumard oak's place in the ecological succession of oak-hickory climax communities has not been clearly defined. On the drier habitats west of the Mississippi River, it shows some evidence of being a climax tree.

OAK, SOUTHERN RED (*Quercus falcata* Michx. var. *falcata*)

Southern red oak (typical variety) is one of the commonest of the upland southern oaks. Prevalent throughout the forested South except in peninsular Florida, the high Appalachians and the Mississippi Delta, it also occurs northward to the Ohio River and Long Island. In the South Atlantic States it is abundant in the Piedmont, but less frequent in the Coastal Pine Belt.

Southern red oak is characteristically an upland tree occurring on dry, sandy or clay soils. It is also found widely on sandy loam, sandy clay loam, and silty clay loam soils. Occasionally this tree occurs along streams in fertile bottoms where it attains its largest size.

Throughout its range, southern red oak is most frequently found at elevations below 2,000 feet. It usually grows on dry ridgetops and south or west facing upper slopes, rather than on the more moist lower slopes, bottom lands, or north and east aspects.

About 84 percent of total southern red oak volume in the South is on southern pine sites (tables 2-7 through 2-18). Pine site concentrations are greatest in counties of east Texas, north west Louisiana, southern Arkansas, Mississippi, Alabama, North Carolina, and Virginia (fig. 3-22). Total pine-site volumes of southern red oak are greatest in Alabama, Arkansas, Mississippi, Louisiana, and Georgia (602, 589, 568, 446, and 418 million cubic feet, respectively). Somewhat lesser pine-site volumes occur in North Carolina, Texas, and Virginia (357, 343, and 285 million cubic feet). Least pine-site volumes of southern red oak grow in South Carolina, Tennessee, Florida, and Oklahoma (170, 132, 49, and 35 million cubic feet).

Flowering of southern red oak occurs during April and May throughout most of the range. Its fruit ripens in September and October, the second season after flowering, and seedfall occurs during these months. Seed production usually begins when a tree is about 25 years of age, but maximum production usually occurs between the ages of 50 and 75 years. Dissemination of acorns by gravity is important on steep slopes. The hoarding habit of squirrels is important in the dispersal of seed of many nut trees, and southern red oaks are no exception. The seed of southern red oak germinate under natural conditions in the spring following seedfall, but the specific requirements for germination and survival of the seedlings have not been studied.

Southern red oak sprouts vigorously from the stump when the top has been killed or cut back, especially on young stems 10 inches or less in diameter. This tree, like most of the oaks, is difficult to propagate by cuttings.

At maturity, southern red oak is a medium-sized tree, usually from 70 to 80 feet in height and 2 to 3 feet in diameter. In forest stands it develops a long, straight trunk and upward reaching limbs that form a high, rounded crown. Maximum age attained is about 150 years. No data on growth rates and yields have been compiled for this species.

Diameter growth of small southern red oaks on pine sites probably averages less than 2 inches in 10 years. A sample of 10 southern red oaks (5.6 to 6.5 inches in dbh) collected from pine sites throughout the species' southern range averaged 35 years of age, 6.0 inches in dbh, and 43 feet in height (table 3-1).

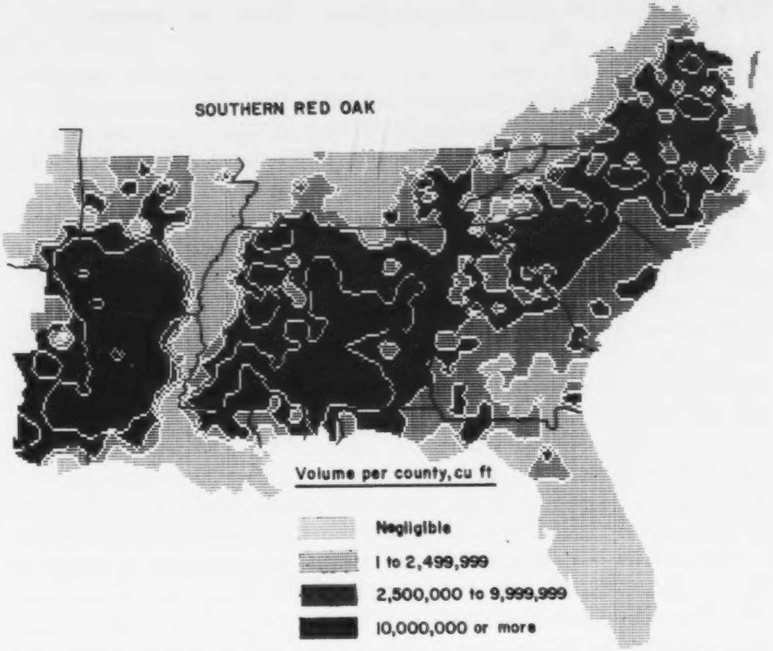

Figure 3-22.—SYMAP computer map of distribution and concentrations of southern red oak (*Quercus falcata* Michx. var. *falcata*) on pine sites. (Drawing after Christopher et al. 1976.)

Southern red oak is rated, in comparison with its associates, as intermediate in tolerance or intolerant. Epicormic branching is very profuse on this species, especially in crop trees recently released. This reduces the quality of the timber and suggests that good quality requires dense stands.

Southern red oak is susceptible to injury by fire because of its thin bark. As a result of fire scars and other injuries, trees are often subject to heart rots.

OAK, WATER (*Quercus nigra* L.)

Water oak is found along small streams, on the margins of Coastal Plain swamps, on bottom lands, and on deep or moist upland soils in most of the forested South; it is scarce or absent in the Ozarks, eastern Tennessee, western North Carolina and Virginia, and in lower Florida. Its best development is in the southern and southeastern parts of its range.

Water oak grows on a variety of bottom land soils and on some upland soils. When it grows on uplands, quality of the tree is poor except on moist lower slopes of rough terrain. On alluvial bottoms, the better-drained silty clay or loamy ridges, and the borderline sites between flats and ridges, it is often an excellent timber tree. On poorly drained clay flats in the bottoms, form and quality are poor.

About 47 percent of total water oak volume in the South is on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations are greatest in counties of east Texas, Louisiana, southern Arkansas, Mississipi, Alabama, and eastern portions of North and South Carolina (fig. 3-23). The greatest total volume on pine sites is in Georgia (459 million cubic feet) followed by Alabama with 379 million cubic feet. Next are North Carolina, South Carolina, Louisiana, Texas, and Mississippi with pine-site volumes of 293, 268, 254, 219, and 217 million cubic feet, respectively. Southern States with least volume of water oak on pine sites are Arkansas, Florida, Virginia, Oklahoma, and South Carolina (112, 104, 20, 6, and 1 million cubic feet).

Water oak flowers from February to May, shortly before the tree leafs out. Near Stoneville, Miss., at latitude 33½°N, flowering usually begins the first or second week in March, a week or two before leaves open. The fruit matures between August and October of the second year. Infrequent late freezes, after the flower and leaf buds have opened, kill the flowers and defoliate the trees. New leaves will develop after the frost, but a second crop of flowers is not produced.

Seed production begins when the trees are about 20 years old, and good crops are borne nearly every year. Mature trees may produce ¼ to 1½ bushels of fruit per year. There are 300 to 700 seeds per pound. Seed is disseminated by animals and by water.

Water oak seed germinates the spring following seed fall. The best seedbed is a moist, well-aerated soil with an inch or more of leaf litter. At Stoneville, Miss., after 48 days of stratification, 80 percent of water oak acorns germinated in 69 days, with first germination in 28 days. After 108 days' stratification, germination was 80 percent in 24 days, with first germination in 10 days. Unstratified seed germinated 80 percent in 86 days, with first germination in 47 days.

The survival and early growth of water oak is best when moisture is abundant throughout the growing season. Early height growth on good sites is about 2 feet per year in the first 25 years, even when competition from weeds and vines is severe.

Although water oak readily sprouts from young stumps, vegetative propagation by cutting is very difficult.

Under favorable conditions water oak develops a straight, tall, slender trunk. In the forest it is frequently 100 to 125 feet tall on good sites, but is usually slow to prune itself. It grows rapidly on good sites. Trees 6 to 12 inches dbh in natural unmanaged stands in the north Louisiana Delta average 2.6 inches of diameter growth in 10 years. In the 14- to 18-inch class they will grow 3.1 inches in 10 years; in the 20- to 28-inch class, 2.9 inches. In a study of 295 water oaks in south Georgia, 10-year diameter growth was 2.1 inches in trees 6 to 8 inches in diameter, 3.7 inches in 10-inch trees, and about 2.5 inches in trees 12 to over 20 inches in dbh (Cruikshank 1952).

Growth is less rapid in small water oaks over a spectrum of southern pine sites. A sample of 10 water oaks 5.5 to 6.3 inches in dbh collected from southern

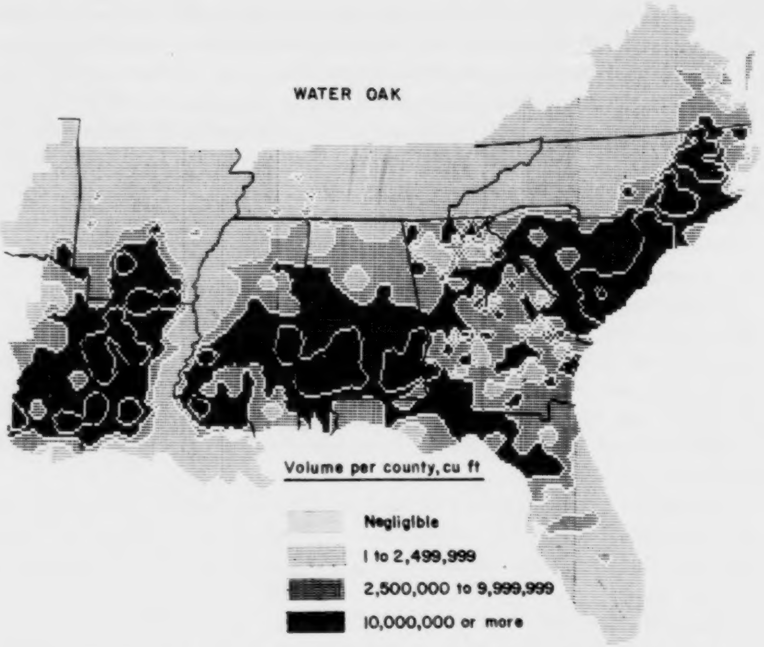

Figure 3-23.—SYMAP computer map of distribution and concentrations of water oak (*Quercus nigra* L.) on pine sites. (Drawing after Christopher et al. 1976.)

pine sites throughout the species' southern range averaged 39 years of age, 5.9 inches in dbh, and 54 feet in height (table 3-1).

Broadfoot (1963) observed that site index for water oak can be gaged by three methods: (1) estimated from amount of sodium in the soil, depth of topsoil, and presence or absence of a hardpan; (2) determined in the field from soil texture, depth to mottling, presence of a pan, depth of topsoil, and inherent moisture condition; (3) read from a table of averages after soil series and phase have been identified. For the Midsouth, tree height and age are related to site index (tree height in feet at age 50) as follows:

	Tree height at 2 ages	
Site index	30 years	60 years
Feet	----------*Feet*----------	
60	45	63
70	53	74
80	61	84
90	68	95
100	77	105
110	87	116

Water oak is intolerant and a subclimax tree. It germinates well under moderate shade, but the seedlings grow little without release. Suppressed trees of low vigor are very subject to epicormic branching after release.

McKnight (1958) summarized tentative conclusions concerning the thinning of water oak, He noted that water oak is inherently limby; it should therefore be grown in dense, nearly even-aged groups occupying a fifth acre or more, until trees reach pole size. Then they can be released. On best sites and with adequate space, water oak grows rapidly. Trees should be favored through judicious release where they are competing with less desirable stems of their own or other species. As far as possible, trees picked for growers should be those with full, healthy crowns in the dominant or codominant positions. Slow-growing trees, and those with epicormic branches or severely damaged crowns or trunks, should be harvested if possible. Partial cutting merely to reduce levels of stocking should be confined to even-aged patches. Such cutting is likely to take on the nature of all-aged selection or improvement cutting as sawtimber begins to develop.

Water oak is susceptible to damage by fire at all ages. Even a very light burn will kill the stems of all seedlings and small saplings, and more intense fires may kill much larger trees. Trees not killed are frequently damaged so that they are subject to serious butt rot.

OAK, WHITE (*Quercus alba* L.)

White oak grows throughout the forested South except peninsular Florida, parts of the lower Coastal Plain, and the Mississippi Delta. Its range extends north into southern Ontario, Quebec, and central New England. The west slopes of the Appalachian Mountains and the Ohio and the central Mississippi valleys have optimum conditions for white oak. The largest trees, however, have been found in Delaware and on the eastern shore of Maryland.

White oak grows on a wide range of soils and sites. It is found on some Podzols, Gray-Brown Podzolic Soils, Brown Podzolic Soils, Red and Yellow Podzolic Soils, Lithosols, Planosols, and Alluviums. The tree grows on both glaciated and nonglaciated soils derived from many parent materials. It is found on sandy plains, gravelly ridges, rich uplands, coves, and well-drained second bottoms. The species develops best on deep, well-drained loamy soils, but growth is good on all except the driest, shallow soils.

Mineral nutrition is not limiting to white oak growth except on very sandy soils. In one study, the mineral content of leaves was not correlated with that in the A horizon soil. White oak leaves on the most productive soils were only slightly richer in minerals than those on the poorest soils. Apparently white oak assimilates sufficient minerals from even the poorer soils.

In a Piedmont study, the soil factors most important to growth rate were thickness of the A_1 and A horizons and the location of the tree on the slope. In the brown loam area of north Mississippi and west Tennessee, factors best correlated with site factor were: percent clay in the surface soil, depth to the least permeable horizon, 15 atmosphere tension value of the least permeable horizon, and position on slope (McClurkin 1963).

White oak grows on all upland aspects and slope positions, including ridgetops except extremely dry, shallow-soil ridges, poorly drained flats, and wet bottom lands. It grows best on northerly and easterly lower slopes and coves, and well on moderately dry slopes and ridges having shallow soils. Although of smaller size on the drier west- and south-facing slopes, white oak is more abundant there than on the mesophytic sites. In the central and southern part of its range, altitude is seldom limiting. In the Southern Appalachians, it is a scrub tree at elevations of 4,500 feet.

About 65 percent of total white oak volume in the South is on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations of 10 million or more cubic feet are found in some counties of all Southern States except Florida (fig. 3-24). Greatest pine-site volumes of white oak are in Virginia and North Carolina (1,149 and 1,022 million cubic feet, respectively). Substantial pine-site volumes also grow in Arkansas, Alabama, Georgia, and Mississippi (893, 633, 573, and 438 million cubic feet). Lesser volumes are on pine sites in South Carolina and Texas (287 and 180 million cubic feet). Oklahoma and Florida have least white oak growing on pine sites (62 and 8 million cubic feet).

White oak flowers appear with the new leaves from late March to late May, depending upon the latitude. Dry winds and freezing weather are detrimental to male flowering and pollen dispersal. Acorns ripen in 6 to 8 months, drop in late September and October, and germinate almost immediately.

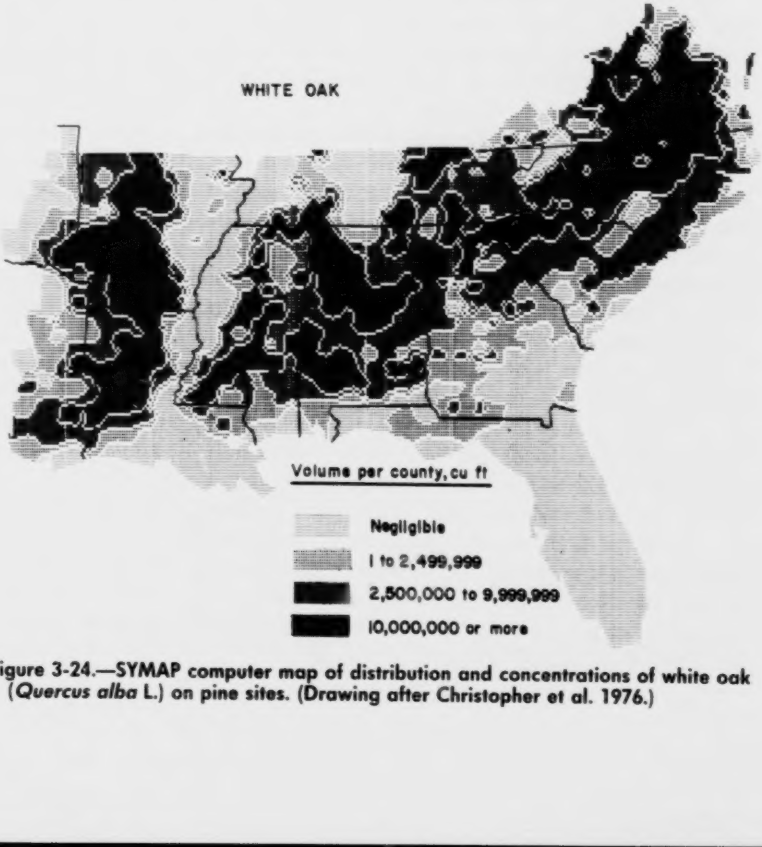

Figure 3-24.—SYMAP computer map of distribution and concentrations of white oak (*Quercus alba* L.) on pine sites. (Drawing after Christopher et al. 1976.)

White oak is often a prolific seeder, but good acorn crops are irregular—they occur 4 to 10 years apart. Sometimes several years may pass without a crop. Trees normally bear seed between the ages of 50 and 200 years, sometimes older; however, open-grown trees may produce seed in as soon as 20 years.

Acorn yield per tree is extremely variable. On three experimental areas in Missouri, the average number of mature acorns per tree per year varied from 0 to 1,900 over a 6-year period. In one county the average number per tree was 700 and in another county 1,100. The best producing tree had 7,700 acorns per year. Trees were either consistently good or poor seed producers from year to year. Crown size was a significant factor in acorn production, but other differences tended to obscure its effect. In the Southern Appalachians the average 16-inch tree bore 700 acorns per year. Trees 24 to 26 inches in diameter averaged 2,000 acorns. Larger trees, however, had fewer acorns.

Sound white oak acorns have a germination capacity between 75 to 95 percent. The seed germinates in the fall soon after dropping, requiring no pretreatment. Germination is good when the temperature is about 65°F during the day and about 50° at night. When the moisture content of the embryo falls to less than 50 percent of the dry weight, viability is greatly reduced. Hence, a cover of litter on the ground soon after the acorns fall is desirable. This usually happens in forest stands because leaf fall continues for some time after the acorns fall.

In one study, less than 40 percent of acorns produced were fully developed, and only 46 percent of mature acorns were sound; 30 percent were damaged by insects and 24 percent by animals. Thus, of the total seeds produced, only about 18 percent were sound and fully developed. In a Missouri study, only 14 percent of the mature acorns were sound. However, some damaged acorns will germinate if the embryo is not damaged. Light acorn crops are usually completely destroyed by insects and animals, so seedlings are usually produced only during years of heavy crops.

Seed dissemination is by squirrels, gravity, and wind. Except for seed transported by squirrels, the seeding range is small. Widespread reproduction depends on large numbers of seedbearing trees.

After acorns germinate in the fall, growth of the radicle continues until interrupted by cold weather. In the spring the seedling develops a strong taproot, usually more than a foot long and ¼ to ½ inch in diameter. This early access to deeper moisture makes white oak seedlings less sensitive to near-surface drought than some competitors.

Where climate and soil are favorable for germination and growth, white oak will reproduce adequately from seed if: (1) there are large seed trees within about 200 feet; (2) there is a light to moderate (but not thick) litter cover; and (3) there is full sunlight at least part of the day. The minimum opening for good seedling growth has a diameter equal to the heights of the surrounding trees. The average light in such an opening varies from 35 to 55 percent of full sunlight.

On better sites white oak outgrows post and blackjack oak. On the driest sites, however, post and blackjack oak prevail because they are less susceptible to drought injury.

Young white oak trees sprout prolifically and vigorously when cut or badly damaged by fire. This ability to sprout is retained in trees up to at least 80 years old. Much existing second-growth white oak originated from sprouts following cutting or fire. Low stump sprouts from pole-size trees and seedling sprouts are about as good as trees from seed. Sprouts originating high on the stump are likely to have heartwood decay. Frequent fires and continual grazing of seedlings often result in the formation of root stools under the ground surface, which sprout abundantly when protected..

Even in the absence of fire and grazing, reproduction persists under the forest canopy in the form of seedling sprouts. The roots live and increase in size for many years although the tops may die back every few years. Opening the stand by cutting results in rapid growth of the seedling sprouts present. These sprouts are usually free from decay. A survey in Missouri showed that 57 percent of white oak reproduction was composed of sprouts.

White oak is generally reputed to be slow growing. This is only partly deserved. Early growth may be slower than for some associated trees, and overtopped white oaks may persist for a long time. When not overtopped, white oak grows faster in height than hickories, nearly as fast as black oak and southern red oak, although somewhat slower than yellow-poplar.

Diameter growth follows a similar pattern. In the Tennessee Valley, sawtimber-sized white oak grew slower than yellow-poplar and scarlet oak, about the same as black oak, and faster than hickory. Growth averages from Forest Survey data on white oak in the Central States range from 1.4 (Missouri) to 2.1 (Indiana) inches of diameter growth in 10 years. The average of 1.8 for all States was about the same as that for black oak, slightly less than for scarlet oak, 0.6 inch less than for yellow-poplar, but 0.4 inch greater than for hickory.

On southern pine sites Southwide, ten-year diameter growth of small white oaks is probably less than the 1.8 inch average noted above. A sample of 10 white oaks (5.6 to 6.2 inches in dbh) collected from southern pine sites throughout the species' southern range averaged 42 years of age, 5.9 inches in dbh, and 47 feet in height (table 3-1).

On good sites, white oak is a large tree. It normally reaches 100 feet in height and 4 feet in diameter on such sites. Trees 150 feet tall, 8 feet in diameter, and 600 years old have been found. In the open, white oak develops a short, stocky bole with a very wide-spreading, robust crown. In the forest, it grows tall and straight with a narrow crown.

White oak normally grows in mixed, uneven-aged stands, but even-aged mixed oak or pure white oak forests may develop after clear cutting. Individual trees may contain 1,000 board feet or more, but this is not common. Pure and mixed stands will normally contain from 2,000 to 12,000 board feet per acre, occasionally more. Except on the poorest sites, growth of managed stands will vary from 150 to 600 board feet per acre per year with a rotation of 80 to 100 years for sawlog production. Unmanaged stands may yield much less. Fully stocked, normal even-aged stands of mixed oak are reported to yield 6,380 cubic feet at age 100 on site index 80.

In the Southern Appalachians and in the Piedmont, the site index for white oak is generally less than for yellow-poplar and other important oaks on the same site. On all these sites the index for white oak is higher than that of shortleaf pine (*Pinus echinata* Mill.). And, on the poorest sites, the index for white oak is higher than that for yellow-poplar.

A study of 136 white oaks in the Boston Mountains of Arkansas showed height growth related to tree age and site index (tree height in feet at age 50) as follows (Graney and Bower 1971):

Site index	Tree height at 2 ages 20 years	 100 years
Feet	--------*Feet*--------	
40	20	48
50	24	69
60	28	89
70	32	109
80	37	125

White oak, when associated with other oaks and hickory in the central and southern hardwood forests, is considered a climax tree. It usually tends to become dominant in the stand, at least within its optimum range. Reasons for this are: (1) its ability to live vigorously for long periods as an overtopped tree; (2) its ability to respond quickly to release; (3) its moderately fast growth rate in full sunlight; and (4) its great longevity.

Natural pruning of white oak is usually good in moderate to heavily stocked stands. Large, dominant trees have cleaner boles than smaller trees in lower crown classes. There is a tendency for some branches along the trunk to persist if strong side light is present. Epicormic sprouting may be heavy on suddenly released trees, especially if they were slow growing. Large, vigorous trees seldom develop epicormic branches when exposed to full light, but branches already present will persist and increase in size.

Live branches not more than 1½ inches in diameter may be saw-pruned without danger of introducing rot. However, epicormic sprouts will often develop around the edges of the wound on saplings and small pole-size trees. Bole sprouts usually do not develop in vigorous, dominant pole-size trees.

Decay of heartwood resulting from fire scars causes the most serious losses in white oak. The amont of decay following basal fire scars depends upon: (1) the size of the wound, (2) the species of fungi involved, and (3) length of time since wounding. In general, rot continues to increase if the basal scar is more than a foot in diameter. The larger the wound, the faster the increase of rot.

SWEETBAY (*Magnolia virginiana* L.)

In the lumber trade, the woods of sweetbay (*M. virginiana* L.) and southern magnolia (*M. grandiflora* L.) are both sold under the designation **magnolia**. Magnolia wood is moderately hard, fine-textured, straight-grained, and easy to machine; it glues well, and stays in place well. Its heartwood is light to dark yellowish-brown, with a greenish or purplish tinge—sometimes containing black, dark brown, or even rainbow-colored heartwood streaks; magnolia sapwood is a very pale yellow to creamy white. It is a good furniture wood, but is separated for color when uniformity is required for exposed furniture parts (Southern Hardwood Lumber Manufacturers' Association (n.d.a, b)). In the South, trees of both species retain green leaves all year long.

A third member of the genus, cucumber tree (*M. acuminata* L.), is also traded on the lumber market. Unlike the magnolia of commerce, the cucumber tree has thin leaves which turn yellow and drop in the fall, and its wood resembles yellow-poplar so closely that it is sometimes mixed and sold with yellow-poplar (Southern Hardwood Lumber Manufacturers' Association (n.d.a, b)). The cucumber tree is found sparingly throughout the Appalachian Region extending south into Georgia and into small discontiguous areas west in Louisiana and Arkansas.

Sweetbay and southern magnolia both occur rather sparsely over the southern Coastal Plain, and extend further inland near the Mississippi River to southern Arkansas and Tennessee. Sweetbay extends locally along the Atlantic Coast to Massachusetts; southern magnolia is not native north of southern Virginia.

Greatest volumes of the three commercial magnolias are found near the Gulf Coast in Mississippi, Alabama, and the Florida panhandle (fig. 3-25). In the Midsouth, survey data indicate that 77 percent of all magnolia volume is sweetbay. For this reason, discussions that follow in this text apply primarily to sweetbay, rather than southern magnolia.

There is little published information on the soils preferred by sweetbay, but the tree occurs in moist soils in bottoms along waterways in pine woods. It is usually not found on the higher drier sites where pine predominates. Kral (1961) notes that sweetbay is common on soils that are poorly drained or often flooded; such sites are usually acid, but the species also grows in alkaline soils of ravines and hammocks.

About 20 percent of total sweetbay volume in the South is on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations exceeding 2.5 million cubic feet are reported in counties along the Mississippi, Alabama, and Florida Gulf Coast, and in west-central Louisiana and central Alabama (fig. 3-26). Total pine-site volume of sweetbay and southern magnolia is greatest in Alabama (82 million cubic feet) followed by Mississippi and Florida (63 and 60 million cubic feet, respectively). Georgia and Louisiana have pine-site volumes of 37 and 36 million cubic feet. Texas, North Carolina, Virginia, South Carolina, and Arkansas have 10, 7, 2, 2, and 1 million cubic feet, respectively. Oklahoma and Tennessee report no surveyed volume of sweetbay on southern pine sites.

Sweetbay and southern magnolia flower in spring and summer. Seeds ripen in late summer and early fall; they are dispersed soon after ripening by wind, birds, and occasionally water. Seeds average about 7,530 to the pound.

The seeds have a dormancy period and over-winter in the duff, then germinate the spring following dispersal. Leaf litter is probably not an impediment to germination.

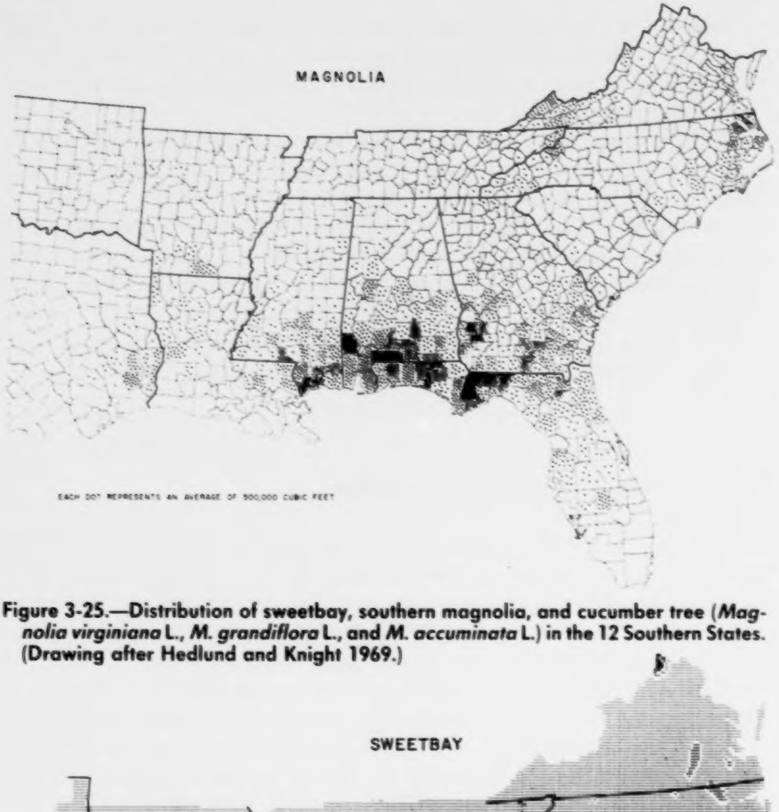
MAGNOLIA
EACH DOT REPRESENTS AN AVERAGE OF 500,000 CUBIC FEET

Figure 3-25.—Distribution of sweetbay, southern magnolia, and cucumber tree (*Magnolia virginiana* L., *M. grandiflora* L., and *M. accuminata* L.) in the 12 Southern States. (Drawing after Hedlund and Knight 1969.)

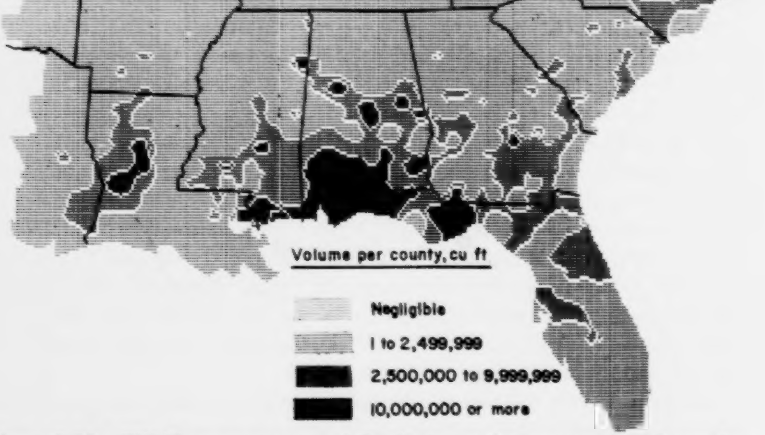
SWEETBAY
Volume per county, cu ft
Negligible
1 to 2,499,999
2,500,000 to 9,999,999
10,000,000 or more

Figure 3-26.—SYMAP computer map of distribution and concentrations of sweetbay (*Magnolia virginiana* L.) on pine sites. (Drawing after Christopher et al. 1976.)

Sweetbay is moderately tolerant to tolerant and grows primarily as an understory plant; it can be found in clumps measuring perhaps 100 feet in diameter. It is a vigorous sprouter and thickets are formed by root sprouts. The tree can be propagated from cuttings.

Sweetbay may reach a height of 60 feet, but it is usually much smaller, in the range from 20 to 30 feet. Most specimens are reported to be less than 5 inches in dbh, with 10-year diameter growth of 1 to 2 inches.

No data are available on the cubic yield of sweetbay, as it does not usually occur in pure stands. A sample of 10 sweetbay trees (5.6 to 6.2 inches in dbh) collected from pine sites throughout the species' southern range averaged 39 years of age, 5.8 inches in dbh, and 45 feet in height (table 3-1).

Sweetbay is susceptible to fire injury. In longleaf and slash pine forest types, burning of shrub bogs causes sweetbay to be replaced by saw-palmetto (Kral 1961).

SWEETGUM (*Liquidambar styraciflua* L.)

Sweetgum is a southern hardwood of major commercial importance. It owes its name to an amber-colored resin (**storax**) that exudes from wounds. In the lumber trade, the wood of sweetgum is separated into **sap gum** cut, as the name implies, from the flesh-colored, light pinkish, or gray sapwood, and **red gum** cut from heartwood. The wood of sweetgum is diffuse porous, with uniform texture. It machines and glues with ease, and accepts paints and finishes well. Consequently, it is much used for furniture (Southern Hardwood Lumber Manufacturers' Association (n.d.a, b)). Interlocked grain is common and contributes to both the difficulty in seasoning the lumber and to a ribbon-stripe figure (Briscoe 1973).

Sweetgum grows throughout the South except along the Appalachian Mountains and in southern Florida. It extends north along the Atlantic Coast to Connecticut, north of the Ohio River into southern Illinois and Ohio, and west of the Mississippi River into eastern Oklahoma and Texas.

On all sites in the 12 Southern States, sweetgum has a wide and relatively uniform distribution (fig. 3-27). About 50 percent of total sweetgum volume in the South is found on southern pine sites. Pine-site concentrations are greatest in a broad band of counties extending across the South from east Texas to central Georgia and northeast to Virginia (fig. 3-28). Total pine-site volumes of sweetgum are greatest in Alabama (950 million cubic feet), followed by North Carolina, Louisiana, South Carolina, and Arkansas (804, 690, 636, and 611 million cubic feet, respectively). Pine-site volumes in Texas, Mississippi, Virginia, and Georgia are also substantial (554, 531, 499, and 459 million cubic feet). Volumes of sweetgum on pine sites are least in Oklahoma, Tennessee, and Florida (32, 53, and 93 million cubic feet).

Sweetgum is very tolerant of different soils and sites but grows best on the rich, moist, alluvial clay and loam soils of river bottoms. It is occasionally dominant on the loessal soils along the east border of the Mississippi River

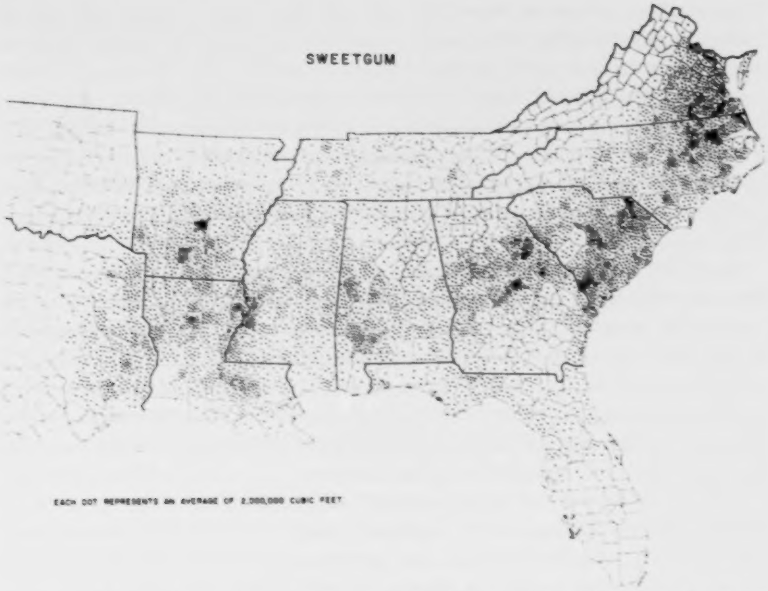
SWEETGUM
EACH DOT REPRESENTS AN AVERAGE OF 2,000,000 CUBIC FEET

Figure 3-27.—Distribution of sweetgum (*Liquidambar styraciflua* L.) in the 12 Southern States. (Drawing after Hedlund and Knight 1969.)

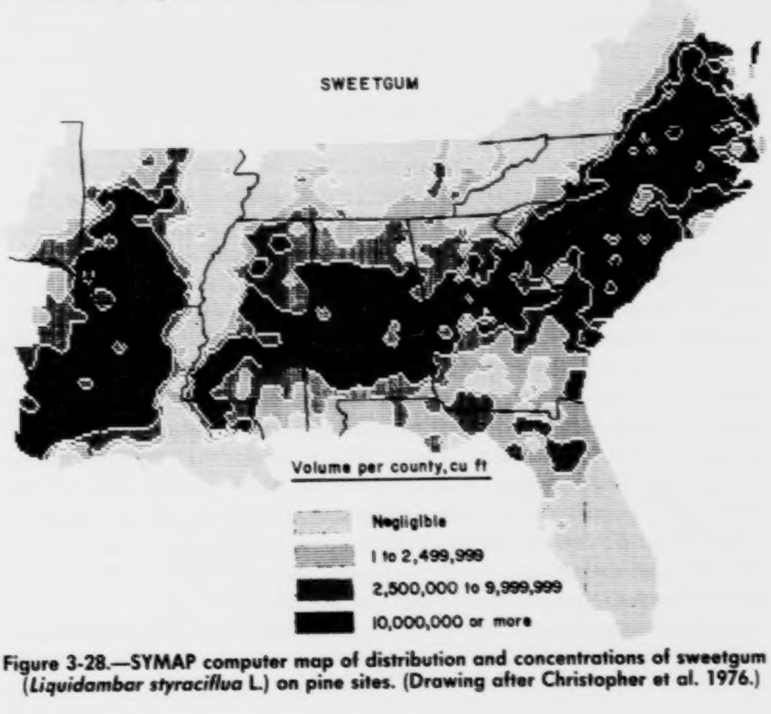
SWEETGUM
Volume per county, cu ft
Negligible
1 to 2,499,999
2,500,000 to 9,999,999
10,000,000 or more

Figure 3-28.—SYMAP computer map of distribution and concentrations of sweetgum (*Liquidambar styraciflua* L.) on pine sites. (Drawing after Christopher et al. 1976.)

Alluvial Plain. On north slopes in the Ozark Mountains, sweetgum is only a minor component of the stand and does not show dominance; here it is always associated with soils derived from chert.

In the Appalachian Valley, the best sweetgum sites are those suitable for yellow-poplar, but sweetgum is not as demanding as yellow-poplar. In the lower Mississippi Valley, site index for sweetgum increases with the amount of exchangeable potassium in the soil and decreases as clay percentage increases. The best sites are those with medium textured soils without a hardpan in the top 2 feet, and with moderate to good internal drainage.

Sweetgum flower buds are extremely sensitive to cold, and therefore are often damaged by frost. The flowers appear from March to May, depending on latitude and weather. In the fall, the fruit turns yellow; the seeds mature from September to November. Soon after maturing, the seed is disseminated by the wind; however, the empty fruits often remain on the tree for the entire winter.

The tree begins to produce seed when 20 to 30 years old, and crops remain abundant until about 150 years. Fair seed crops are produced each year, with bumper crops every two or three years.

Under conditions of full sunlight and rich soil, each fruit may average as many as 50 sound seed. Under average conditions, only seven or eight sound seeds per fruit are produced. One bushel of fruit will yield 12 ounces of seeds (approximately 60,000). The maximum distance of seed dispersal recorded is 600 feet, but ordinarily 96 percent of the seed falls within 200 feet of the point of release.

Sod is not a serious hinderance to seed germination. However, when additional sweetgum reproduction is desired in partially cutover stands, exposed mineral soil and abundant direct sunlight are necessary. Root development varies with the growing site. A deep taproot and numerous horizontal rootlets usually develop early, but in wet areas roots are shallow and wide-spreading, with little or no taproot. On gravelly ridges and hillsides, sweetgum develops a particularly strong taproot and is very wind resistant.

A wide-range provenance study indicated that genetic gains should be possible by selecting the best stands, and then selecting seed from the best trees within those stands (Sprague and Weir 1973). About 35 percent of sweetgum crown cuttings, to which rooting powder had been applied, were rooted in 2 months (Hare 1976). Root cuttings can also be used to propagate sweetgum (Brown and McAlpine 1964).

Sweetgum is capable of sprouting until it is approximately 50 years old. The season of cutting has no effect on the number of sprouts. Shortest sprouts develop on stumps cut in May and August. Sprout vigor does not decline until the third generation of successive generations of sprouts from the same stump.

Sweetgum seedlings reach a height of 4.5 feet in 3 to 5 years; sprouts often reach this height in 1 growing season. Ten-year-old sprouts may have the same size as 18- to 20-year-old seedlings in the same stand. Double stems in a 99-year-old stand indicate that sweetgum sprouts can grow into sawtimber; many old-field stands originate largely from root sprouts.

Young sweetgums have long conical crowns that usually prune themselves readily under forest conditions. The branches of young trees are at an acute angle to the stem. Mature trees have crowns that are round and spreading; the tops of overmature trees are usually broken or stag-headed. The species responds slowly to release, except when young or below 10 inches dbh.

Heights of 150 feet and diameters to 60 inches may be attained by sweetgum growing in Mississippi River bottoms. In well-drained uplands (Maryland), heights of 65 feet and diameters of 18 to 25 inches are attained.

A tendency to fork limits clear lengths; in South Carolina and Missouri the maximum length of clear stem observed was 58 feet, for trees approximately 16 inches dbh and larger.

Average 10-year-diameter growth for overmature sweetgum has been reported at 1.9 inches. In South Georgia, sweetgum 6 to 10 inches in dbh also had diameter growth of about 1.9 inches in 10 years; 12-inch trees grew 3.2 inches, while 14-, 16-, 18-, and 20-inch trees grew 2.2, 2.1, 1.9 and 1.6 inches in 10 years (Cruikshank 1952).

Ten-year diameter growth of small sweetgum on a range of southern pine sites may average about 2 inches. A sample of 10 sweetgum trees (5.5 to 6.2 inches in dbh collected from pine sites throughout the species' southern range averaged 29 years of age, 5.9 inches dbh, and 47 feet in height (table 3-1).

Broadfoot and Krinard (1959) have related index in the Midsouth (tree heights in feet at age 50) to sweetgum tree age and height as follows:

	Tree height at 3 ages		
Site index	20 years	30 years	65 years
Feet		*Feet*	
70	—	54	75
80	46	60	87
90	52	67	99
100	58	74	111
110	64	83	122

Readers desiring additional information on site index curves and tree volumes for sweetgum will find Broadfoot (1970), Lyle (1973), and Lyle et al. (1975) useful.

In the Mississippi Delta, pure stands of sweetgum average 6,000 to 8,000 board feet per acre. Very good stands will have 15,000 to 20,000 board feet per acre, with 30,000 to 40,000 board feet found on small selected areas. Ridges usually have lighter stands than the flats. In virgin stands of mixed bottom land hardwoods, sweetgum averages 5,000 to 6,000 board feet per acre.

In pure stands on bottom land sites, young sweetgum is able to endure some shade and stand some crowding. With increased age the trees become less tolerant of competition. Following the natural decrease in the density of the crown canopy, enough sunlight reaches the ground to permit an understory stand to develop. In upland southern pine stands, sweetgum seedlings or sprouts are often present in the understory. Removal of the pine overstory results in rapid growth of the sweetgum.

Fall frosts often kill the late summer shoot growth of sweetgum. Seedlings may be badly damaged by hogs, goats, or cattle. Rodents, particularly mice and rabbits, have caused considerable damage to young seedlings in plantations. For example, young sweetgum plantations in the Appalachian Valley of eastern

Tennessee grow well on the better sites, but field mice kill so many seedlings that its use is inadvisable in planting except on good sites in rodent-free areas.

Sweetgum is very resistant to disease and insect attack, but it is highly susceptible to death or injury by fire. Summer fires damage understory sweetgum more than winter fires. One year after three successive summer fires, 33 percent of the sweetgums were dead.

Fire scars on living trees furnish entrance points for insects and fungi. If sapwood is not killed, these agents may be excluded by gum exudation. Repeated fires, however, usually kill some sapwood, permitting fungi and insects to become established. In the lower Delta of the Mississippi River, 42 percent of once-burned sweetgum trees showed decay 8 years later; 79 percent of those burned repeatedly during an 8-year period showed decay.

TUPELO, BLACK (*Nyssa sylvatica* Marsh.)

Four tupelos are recognized in the United States. They are water tupelo (*N. aquatica* L.), Ogeechee tupelo (*N. ogeche* Bartr.), and two varieties of black tupelo (*N. sylvatica* Marsh.). In the South, tupelo species are most heavily concentrated in the Coastal Plains from Mississippi to Virginia; substantial volumes, however, are uniformly distributed across the Southern States, including the Highland Region, from eastern Texas and Oklahoma to Virginia (fig. 3-29). Because black tupelo is the species most frequently found on southern pine sites, the following discussion is limited to this species.

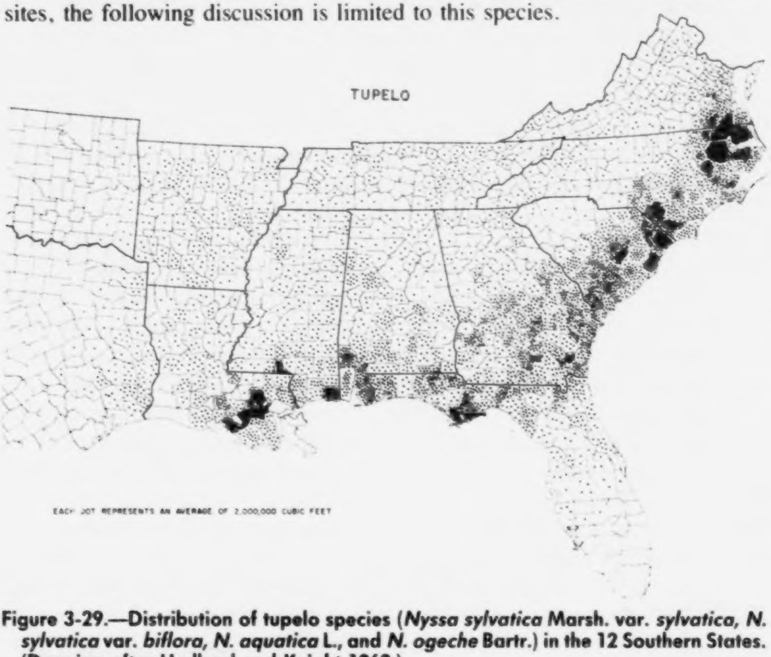

Figure 3-29.—Distribution of tupelo species (*Nyssa sylvatica* Marsh. var. *sylvatica*, *N. sylvatica* var. *biflora*, *N. aquatica* L., and *N. ogeche* Bartr.) in the 12 Southern States. (Drawing after Hedlund and Knight 1969.)

Black tupelo, also known as **black gum** in the lumber trade, is utilized for long-fibered hardwood pulp and for containers; it is also much used in the furniture industry because the sapwood—which predominates in today's logs—is a creamy off-white color that lends itself to currently popular light finishes. The heartwood is light brownish-gray. Black tupelo is diffuse porous with close, uniform texture, and indistinct annual rings; its interlocked grain, which is not inclined to split, calls for careful drying to minimize warp. The wood is moderately heavy and machines and glues well (Southern Hardwood Lumber Manufacturers' Association (n.d.a, b)).

Black tupelo is divided into two distinct and commonly recognized varieties, typical black tupelo (*N. sylvatica* var. *sylvatica*) and swamp tupelo (*N. sylvatica* var. *biflora* (Walt.) Sarg.). Both varieties may be found in bottom lands and swamps, but the typical variety is also common on many upland sites. Typical black tupelo ranges throughout the forested South except in far southern Florida and the Mississippi Delta. Its range also extends north into New England, Ontario, and southern Michigan. Swamp Tupelo is confined mainly to the southern coastal plain, and as the name implies, occurs primarily on wetlands. Typical black tupelo is the variety that is generally found on southern pine sites.

Black tupelo grows well on well-drained, light-textured soils on the low ridges of second bottoms and on the high flats of silty alluvium. In the uplands it grows best on the loams and clay loams of lower slopes and coves.

It is adapted to a wide variety of sites—from the creek bottoms of the southern Coastal Plain to altitudes of 3,000 feet in North Carolina. It will tolerate brief spring flooding on alluvial sites and is common on the relatively dry upper and middle slopes in the Appalachian Mountains. It will survive, but with a slow growth rate, on the dry uplands of the Coastal Plain, Piedmont, and eastern Great Plains. Swamp tupelo grows on the wetter bottom land soils ranging from the highly organic muck soils to heavy clays in ponds and sloughs, and in low coves and seepages which remain wet the year round. Probably because of better aeration, it achieves its highest growth rate and best form in low coves and seepages. Swamp tupelo tolerates wetter sites than black tupelo, but is not often found in the brakes, sloughs, or deep swamps occupied by water tupelo.

About 29 percent of total black and swamp tupelo volume in the South is on southern pine sites (tables 2-7 through 2-18). Pine-site concentrations are greatest in Coastal Plain counties of Virginia, North and South Carolina, and Georgia; Alabama, Mississippi, east Texas, and Arkansas also have counties with concentrated volumes (fig. 3-30). Total pine-site volumes of black and swamp tupelo are greatest in Georgia (575 million cubic feet) and Alabama (323 million cubic feet). Pine-site volumes in Virginia, Arkansas, Mississippi, South Carolina, and North Carolina range from 204 to 298 million cubic feet. Tennessee, Texas, Louisiana, and Florida have lesser volumes in the range from 111 to 158 million cubic feet. Oklahoma has least (18 million cubic feet).

The flowers of black tupelo appear in the spring when the leaves are nearly grown. The fruit ripens and falls in autumn. The seeds of both varieties are distributed largely by small animals.

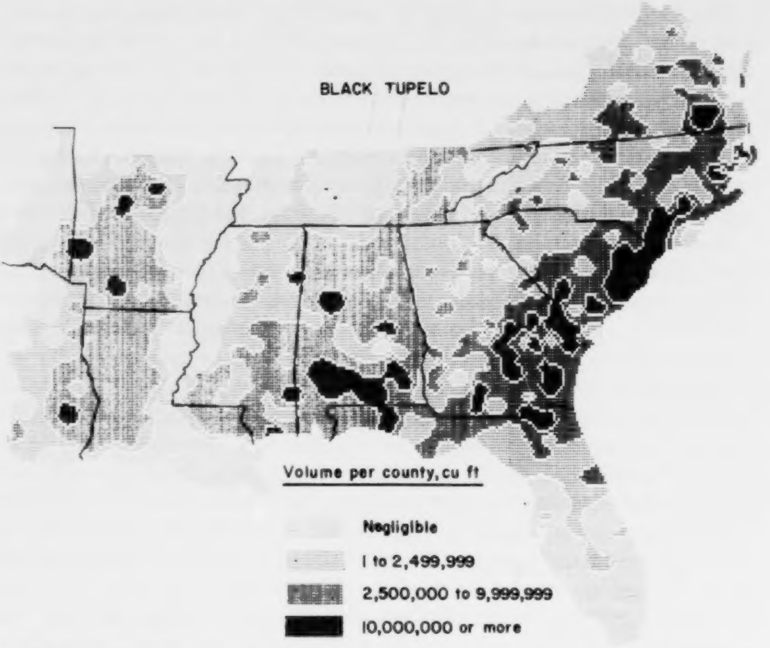

Figure 3-30.—SYMAP computer map of distribution and concentrations of black tupelo (*Nyssa sylvatica* Marsh. var. *sylvatica*) on pine sites. (Drawing after Christopher et al. 1976.)

Under natural conditions, seed overwinters on cool, damp soil and germinates the following spring. Both varieties appear to require nearly full light for optimum early growth. Typical black tupelo, however, will tolerate more overhead competition and can exist on drier sites. Swamp tupelo is much less adaptable.

Layering has been used to produce black tupelo stock and may prove to be a valuable technique after further research. Root suckering may occur around dying black tupelo or near stumps. Swamp tupelo will sprout from stumps of young trees.

Both varieties grow to a mature height of 120 feet with diameters at breast height exceeding 4 feet on favorable sites. Diameter growth on medium sites would average 4 to 5 inches for 10 years. Typical black tupelo on pine sites grows much more slowly, however; small trees may add only one inch of diameter in 10 years. A sample of 10 black tupelo trees (5.5 to 6.2 inches dbh) collected from pine sites throughout the species' southern range averaged 59 years of age, 5.8 inches in dbh, and only 40 feet in height (table 3-1).

The intolerant swamp tupelo often develops in even-aged stands, does not assert dominance, and will stagnate if heavily stocked. Black tupelo usually grows in mixture with other species. It is usually in the intermediate crown class on most sites, rarely attaining dominance within its age group except in the mountains. Both black and swamp tupelo respond slightly to release from a stagnated condition despite long periods of crowding.

Black tupelo, because it grows on drier sites, is more often affected by fire. However, swamp tupelo also suffers from fire when coves and swamps dry out. Hot fires cause severe mortality and cull. Heart rot appears to spread faster in black tupelo than in swamp tupelo.

YELLOW-POPLAR (*Liriodendron tulipifera* L.)

Yellow-poplar is one of the primary commercial hardwood species in the United States because of its availability, rapid growth, excellent form, clear bole, and good working properties. It was second only to oak in lumber production in 1963, and third in hardwood veneer production the same year. The species ranks third in volume of lumber used by the United States' furniture industry, but ranks first in use by the North Carolina industry—the Nation's major producer of wooden furniture (Vick 1973).

In primary manufacture, yellow-poplar is cut principally into lumber, veneer, and pulpwood. The lumber goes mostly into furniture and fixtures, boxes and shook, millwork, core stock for veneer panels, dimension stock, and such miscellaneous products as musical instruments, caskets, toys, and sporting goods. Most veneer goes into plywood—as cross bands, cores, and backs. Much veneer is also used in wirebound crates, and in plywood containers. Pulpwood is converted to paper, mostly by the soda process (Vick 1973).

Heartwood of yellow-poplar is usually tan or greenish-brown, but may be quite variable with shades of purple, dark green, black, blue, and yellow. The coloration apparently has no effect on wood properties, but may be objectionable if natural finishes are applied. The sapwood is whitish and may have a striped appearance. The wood is without characteristic odor or taste. Growth rings are distinct; pores are too small to distinguish with the naked eye and are fairly uniformly distributed throughout the growth ring. Among southern hardwoods it is relatively soft and light in weight (Vick 1973).

Yellow-poplar grows throughout the parts of the South east of the Mississippi Delta except southern Florida; it occurs also in isolated areas of Louisiana and Arkansas. Its range extends north into Michigan, Ontario, and New England.

In the South, heaviest concentrations are in Virginia, and along Tennessee's border with North and South Carolina (fig. 3-31).

Yellow-poplar's optimum development occurs where rainfall is well distributed over a long growing season. In a study in West Virginia, adequate rainfall early in the growing season had more effect on diameter growth than total rainfall during the entire season.

For good growth and form, yellow-poplar is exacting in soil and moisture requirements. Where it occurs naturally, the sites are usually moderately moist, well-drained, loose-textured soils; it rarely grows well in very dry or very wet situations. (An exception is the lower Coastal Plain population in North Carolina

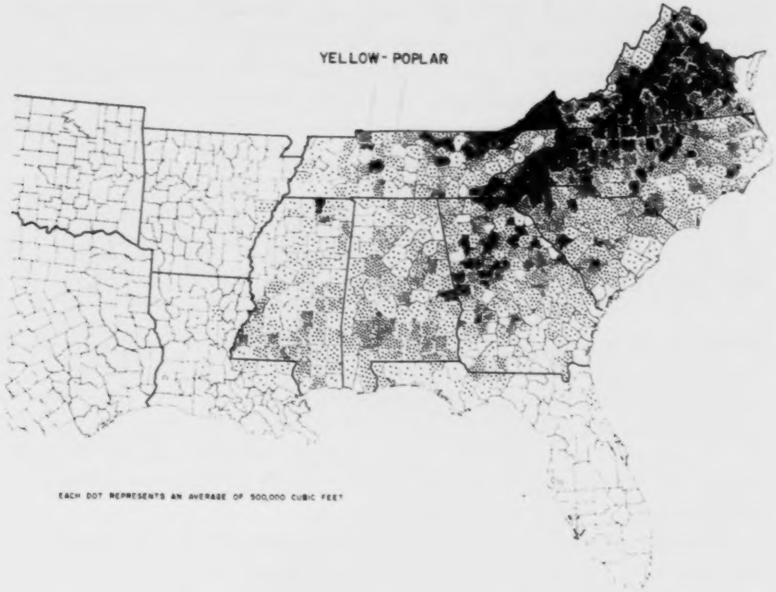

Figure 3-31.—Distribution of yellow-poplar (*Liriodendron tulipifera* L.) in the 12 Southern States. (Drawing after Hedlund and Knight 1969.)

where yellow-poplar grows on very acid, deep-peat soil (Kellison 1967).) Studies in the North Carolina Piedmont showed that site indices of yellow-poplar and loblolly pine were similar on good sites. Two equations for predicting site index of yellow-poplar were developed:

$$\text{Site index} = 110.11 - \frac{101}{\text{Depth of A horizon}} - 198\ (\text{imbibitional water value in B horizon})$$

$$\text{Site index} = 74.88 + 0.7163\ (\text{depth of A horizon})$$

Aspect, position on slope, and elevation all influence yellow-poplar site quality. Confined to elevations below 1,000 feet in the North, it grows in the southern Appalachians on a wide variety of sites including stream bottoms, coves, and moist slopes up to an elevation of 4,500 feet. In Cumberland Plateau plantations yellow-poplar performed about as well as loblolly pine on lower slopes and in bottoms (Smalley and Pierce 1972). Toward the southern limit of the range, where high temperatures and soil moisture probably become limiting, the species is usually confined to well-drained stream bottoms. Growth of planted yellow-poplar in one north Alabama study was best on moist well-drained bottoms (Smalley 1969). In another study in Tennessee and North Alabama (Russell et al. 1970), growth and survival was good on a wide range of wooded sites.

There is evidence that yields of yellow-poplar on moisture deficient and infertile uplands can be improved substantially by combining fertilization with an increased supply of soil moisture (Blackmon and Broadfoot 1970).

About 52 percent of total yellow-poplar volume in the South is on southern pine sites (tables 2-7 through 2-18). Pine site concentrations are substantial in all Southern States except Florida, Mississippi, and those west of the Mississippi River (fig. 3-32). Total pine-site volumes of yellow-poplar are greatest in North Carolina (946 million cubic feet), followed by Virginia and Georgia (805 and 616 million cubic feet). Tennessee, South Carolina, and Mississippi have 278, 210, and 122 million cubic feet, respectively. Florida has 14, Louisiana 10, and Arkansas only 1 million cubic feet, while Oklahoma and Texas have no surveyed volume of yellow-poplar on southern pine sites.

Yellow-poplar flowers from April to June, depending on location and the weather. The flower is one of the favorite sources of nectar for honeybees, and it has been suggested that the number of sound seed is directly related to the number of bees visiting the flowers. About 80 winged carpels are produced in each fruit, and each carpel bears 2 seed, 1 usually aborted. Fruits begin to mature in late September.

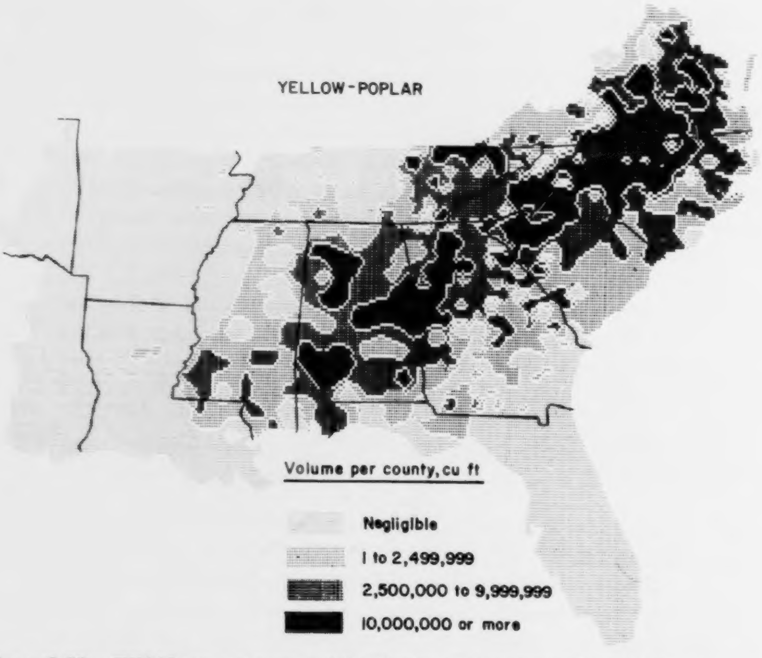

Figure 3-32.—SYMAP computer map of distribution and concentrations of yellow-poplar (*Liriodendron tulipifera* L.) on pine sites. (Drawing after Christopher et al. 1976.)

Although yellow-poplar is a prolific seed bearer, few seeds per strobile are fertile—the rest are empty seedcoats. The minimum seed-bearing age is 15 to 20 years, and the maximum age is known to be more than 200 years.

Bumper seed crops occur at irregular intervals, but a study in North Carolina shows that a fall of 300,000 seeds or more per acre is not uncommon. A 10-inch tree produced about 750 cones with 7,500 sound seeds, and a 20-inch tree produced 3,250 cone with 29,000 sound seed. Cutting tests over 3 years indicated an average of 11.1 percent of all seed were sound. Germination tests, however, usually show lower seed viability than cutting tests.

Individual winged samaras are scattered by the wind to distances equal to four or five times the height of the trees. In a North Carolina study, seedfall began in early October and reached a peak in early November. Sound seeds were disseminated from mid-October to mid-March; seed falling early and late had about the same percentage of soundness. Dissemination is generally highest during warm, dry weather. Much sound seed is eaten by quail, purple finch, cardinal, cottontail rabbit, red squirrel, gray squirrel, and the white-footed mouse.

Clearcutting, seed tree cutting, and group selection have all been used successfully to regenerate yellow-poplar. Since some seed may remain viable for several years on the forest floor, stored seed may greatly augment seedfall at the time of cutting. Essential is continuous moisture for 2 or 3 weeks before germination, best insured by a well scarified seedbed, usually attainable from logging. If yellow-poplar seedlings do not develop adequately the year after cutting, weeds and other plants usually preclude second- or third-year establishment unless the site is re-scarified (Clark 1970).

Yellow-poplar has a rapid growing and deeply penetrating juvenile taproot, as well as many strongly developed and wide-spreading laterals. Attempts to root yellow-poplar cuttings have generally been unsuccessful. Yellow-poplar sprouts readily and vigorously from stumps and frequently develops satisfactorily in clumps, but stands from seedlings are preferable to sprout stands which are apt to develop heart rot, leaving little support against ice and wind damage. Sprouts from small stumps or seedling sprouts have high vigor and usually outgrow the sprouts or seedlings of competing species.

Mature yellow-poplar has reached 190-foot heights and 10-foot diameters, but trees approaching this size are now rare. Good second-growth trees may attain heights of over 120 feet and diameters of 18 to 24 inches in 50 to 60 years. Beck and Della-Bianca (1970) have provided data on cubic-foot yield of wood only (in trees 4.5 inch dbh and larger) to a 4-inch top, measured outside bark, for unthinned yellow-poplar stands of various densities, site indices (height in feet at age 50), and ages; some of their data are condensed as follows:

Trees per acre	Age (years) 20	40	60
Number	*Cubic feet per acre*		
	SITE INDEX 90		
100	520	1,790	3,200
200	650	2,300	3,820
300	800	2,590	—

Trees per acre	Age (years)		
	20	40	60
Number	*Cubic feet per acre*		
		SITE INDEX 110	
100	700	2,730	5,300
200	890	3,650	6,710
300	1,110	4,320	—
		SITE INDEX 130	
100	920	3,990	8,410
200	1,200	5,580	—
300	1,570	6,940	—

Comparable data on thinned stands of yellow-poplar are also available (Beck and Della-Bianca 1972). Additional yield data are available in McCarthy (1933).

Allen and Marquis (1970) found that diameter growth of yellow-poplar increases after thinning, but that height growth of 7- to 9-year-old trees may be markedly reduced after very heavy thinnings. The concluded that stand densities of about 60 percent of normal stocking should be maintained. For thinnning yellow-poplar stands 30 to 70 years old to maximize board foot growth, Della-Bianca (1975) suggests leaving a residual basal area (in dominants, co-dominants, and large intermediates) equivalent to stand site index.

In a study in West Virginia, the average 10-year diameter growth of yellow-poplar by diameter classes was as follows:

Present dbh	Diameter growth in last 10 years
Inches	*Inches*
6	3.55
8	3.37
10	3.19
12	3.00
14	2.82
16	2.64
18	2.46
20	2.28
22	2.09
24	1.91

Among all of the species described in this chapter, small yellow-poplar trees on pine sites made the best diameter growth—about 2.3 inches in 10 years. A sample of 10 yellow-poplars (5.8 to 6.5 inches dbh) collected from pine sites throughout the species' southern range averaged 27 years of age, 6.1 inches dbh, and 54 feet in height (table 3-1).

Data relating tree height at various ages to site index for yellow-poplar in the South can be found in Beck (1962) and Schlaegel et al. (1969). A summary of growth and yield of yellow-poplar and its potential for management is found in Beck (1975), together with citations related to site quality estimation, tree volume equations, stand characterization and structure, and quality data for managed stands.

Although intolerant, yellow-poplar can overcome some competition simply because it grows so fast. In the Piedmont and the mountains of the Southeast, it is extremely sensitive to site change; on the best sites studied, it had the highest site index of all hardwoods and conifers evaluated, and on the poorest sites it had the lowest site index. Successionally, pure yellow-poplar is temporary. Often a pioneer on abandoned or clear-cut land, it is in turn invaded by more tolerant species such as oaks, hickories, or northern hardwoods. More often it regenerates as a mixed type with other species, and it commonly persists in climax stands as scattered individuals.

Yellow-poplar self prunes well except in very sparsely stocked stands; consequently artificial pruning is probably not necesssary in natural stands.

Because of extremely thin bark, yellow-poplar seedlings and saplings are very susceptible to fire damage, and even a light ground fire is usually fatal to stems up to an inch in diameter. On larger trees, when the bark is a half inch or more thick, good insulation is provided against all but the hottest fires.

Sleet and glaze storms, which occur periodically within most of the range of yellow-poplar, may cause considerable damage. Stump sprouts are particularly susceptible to injury and slender trees may be broken. The tops of dominant and codominant trees are often broken, and if breakage is severe the growth rate will be reduced. Although yellow-poplar usually makes remarkable recovery after such storms, repeated damage can result in a serious growth reduction and loss of quality.

Decay often follows top breakage or butt wounds from fire. Dead branch stubs also provide entry points for heart rot in the stem.

3-2 DISTINGUISHING FEATURES OF THE SPECIES[1]

The descriptions, key, and illustrations in this section should help readers, especially those new to the South, to identify hardwood species most prevalent on southern pine sites. Because botanical terms useful in identification comprise a specialized vocabulary, a glossary of terms is included (table 3-2).

TABLE 3-2.—*Glossary of selected botanical terms*

Term	*Definition*
Acuminate	Gradually tapering to a pointed apex
Acute	Having the shape of an acute angle
Aggregate	A cluster of ripened ovaries traceable to separate pistils of the same flower and inserted on a common receptacle
Anther	The pollen-bearing portion of the stamen
Anthesis	Time of flowering
Apetalous	Without petals
Apex	The tip of leaf, twig, or other plant part
Apical	Pertaining to apex

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[1] With minor editorial changes, section 3-2, including illustrations 3-33 through 3-50, is taken from Brown and Grelen (1977) by permission of the authors.

TABLE 3-2.—*Glossary of selected botanical terms*—Continued

Term	*Definition*
Ascending	Growing obliquely or indirectly upward from point of attachment
Axil	Upper angle between a leaf or other plant part and the stem to which it is attached
Bisexual	Having both sex organs on the same plant: a hermaphrodite
Blade	The flat expanded portion of a leaf or parts of a compound leaf
Catkin	A flexible, usually pendulous, scaly spike bearing unisexual flowers
Ciliate	Having a margin fringed with hair
Compound leaf	A leaf with two or more separate leaflets
Cordate	Heart-shaped, with the point at the terminal end
Crenate	Having a margin with rounded to blunt teeth
Cuneate	Wedge-shaped
Deciduous	Not persistent; said of leaves falling in autumn or of floral parts falling after anthesis
Decurrent	With forked stem (see fig. 3-35). Deliquescent.
Dehiscent	Opening by bursting or splitting
Dentate	A margin with sharp teeth pointing outward
Dimorphous	Occurring in two forms
Dioecious	Unisexual, with staminate and pistillate flowers on separate plants
Drupe	A simple one-seeded fleshy fruit, the outer wall fleshy, the inner wall bony
Entire	Margins without teeth or lobes
Evergreen	Having green leaves throughout the year
Falcate	Sickle- or scythe-shaped
Follicle	A dry, single-carpel fruit, opening along one side for seed dispersal
Fluted	Regularly marked by alternating ridges and grooves
Fruit	The seed bearing product of a plant
Glabrous	Smooth, devoid of hair or surface glands
Glandular	Furnished with glands, glandlike
Glaucous	Covered with a white waxy or powdery bloom
Globose	Spherical, globular
Husk	Fleshy covering of nut in hickories
Imbricate	Overlapping
Leaflet	A single division of a compound leaf
Membranous	Thin, more or less flexible, translucent
Midrib	The central rib or central vein of a leaf or similar structure
Monoecious	Having unisexual flowers, with both sexes borne on the same plant
Nut	A hard-shelled, indehiscent, usually one-seeded fruit
Oblique	Slanted; of unequal-sided or non-symmetrical leaves or leaf bases
Obovate	Inverted ovate
Obpyriform	Inverted pear-shaped
Obtuse	Blunt
Odd pinnate	Pinnately compound with a terminal leaflet
Ovate	Having the lengthwise outline of an egg, broadest at the base
Ovoid	Egg-shaped in 3-dimensions
Ovule	An embryonic seed in the ovary of a flower
Palmate	With veins or lobes radiating from a common center
Panicle	A compound or branched raceme
Paniculate	Borne in a panicle
Parted	Divided by sinuses which extend nearly to the midrib

TABLE 3-2.—*Glossary of selected botanical terms*—Continued

Term	*Definition*
Perfect	Having stamens and pistils in the same flower
Persistent	Remaining attached
Petiolate	Having petioles, not sessile
Petiole	The stalk of a leaf
Petiolulate	Having petiolules
Petiolule	The stalk of a leaflet in a compound leaf
Pinnate	Descriptive of compound leaves with the leaflets arranged on opposite sides along a common rachis. Also used to describe leaf venation
Pistil	The seed-bearing organ of the flower
Pistillate	Provided with pistils; usually descriptive of unisexual flowers
Polygamous	Bearing perfect and unisexual flowers on the same plant
Polymorphic	Having two or more forms
Pubescent	Covered with fine, soft, short hairs
Pyriform	Pear-shaped
Raceme	An inflorescence consisting of a central rachis bearing a number of flowers with stalks of nearly equal length
Rachis	The axis of a compound leaf or inflorescence
Receptable	The portion of the floral axis upon which the flowers are borne
Reticulate	Forming a network
Rhombic	Somewhat diamond-shaped
Rib	A prominent vein
Samara	An indehiscent winged fruit
Scurfy	Covered with small scales
Seed	A ripened ovule
Serrate	With sharp teeth pointing forward
Sessile	Without a stalk of any kind
Simple	Of one piece; not compound
Sinuate	Deeply or strongly undulate or wavy
Sinus	A recess, cleft, or gap between two lobes
Spatulate	Spatula-shaped
Spike	An inflorescence consisting of a central rachis bearing a number of stalkless flowers
Stamen	Pollen-bearing organ of the flower
Staminate	Bearing stamens
Stellate	Star-shaped
Stipule	A leafy appendage attached to the twig at the base of a petiole; usually in pairs, one on each side, often shedding early
Striate	With fine grooves, ridges, or lines of color
Suture	Line of dehiscence
Subgloblose	Globe-shaped, but slightly flattened
Subsessile	Almost stalkless
Tomentose	Coated with short matted woolly hair
Truncate	Having a blunt tip or end, appearing as if abruptly cut off transversely
Undulate	Wavy
Unisexual	Having stamens and pistils in separate flowers
Valvate	Opening by valves as in a capsule or some leaf buds; meeting at the edges without overlapping
Whorl	Circular arrangement of appendages at a node
Woolly	Clothed with long, matted hairs

GENERAL DESCRIPTION

Hickories have alternate compound leaves with 5 to 13 leaflets. They are monoecious; that is, the stamens and pistil are borne in separate flowers on the same plant. Flowers generally develop after the leaves are ¾ to full grown. Staminate flowers are in catkins, which occur on last year's wood and usually have three branches. The stalkless pistillate flowers are in several-flowered spikes at the apex of the current season's growth. Catkins last from 10 days to 3 weeks and are usually not useful in distinguishing the species. The fruit, however, is widely used for identification. The husk may be very thin (about 1 mm), moderately thick (3 to 5 mm), or very thick (more than 5 mm). Similarly, the shell may be thin , moderately thick, or very thick. The meat varies from sweet to bitter. Upon drying, the husk usually separates along sutures and frees the nut. In some species the husk partly splits at the sutures but still encloses the nut when it falls. Such nuts are usually sterile, because the meat is seldom filled out.

For identification purposes use nuts from the ground with caution; if more than one species grows in the vicinity, the fruits could be mixed. Also some trees shed defective or sterile fruits early, and these fruits are often different in shape and size from typical fruit.

Hickories are generally divided into true hickories, which have overlapping (imbricate) bud scales, and pecan hickories, which have valvate bud scales. True hickories are divided into those with tight bark and those with loose bark. **Mockernut hickory**, a tight bark species, has very pubescent leaves, large buds, and a thick husk over a large nut. **Pignut hickory**, also a tight bark hickory, has three to nine glabrous leaflets and a tardily dehiscing husk about 3 mm thick. **Shagbark hickory** is one of the few species with bark in thin, loose plates. It has small buds and usually has five leaflets. **Bitternut hickory** belongs to the pecan hickory group and has yellow buds with valvate scales. It also has tight bark, thin four-winged husks, thin shells, and bitter meat.

Oaks are also monoecious, and staminate flowers are in drooping catkins, which consist of a central, flexible axis with sessile apetalous and pubescent flowers. They are most abundant on the developing new twigs. Although catkins vary among oaks, they are usually not used as distinguishing characteristics because they last only 2 to 3 weeks. Pistillate flowers occur on wood of the previous season and in leaf axils of twigs. In red oaks, however, pistillate flowers on current twigs do not mature until the second fall.

The fruit, a nut or acorn, consists of the seed enclosed in a shell. The nut is seated in a cup consisting of many scales. At maturity nuts are shed from the tree by shrinkage of the cup (dehydration). Considerable variation in mature acorn size occurs among trees of a species, notably in water oak, willow oak, and white oak.

Differences in foliage within a species also complicate identification. Apparently because lower leaves receive less sunlight they differ in size and appearance from those in the middle or upper crown. Most taxonomists prefer a specimen from the upper half of the crown because they consider leaves from this area typical for the species. To get such specimens from at least 20 to 30 feet off the ground use a tree pruner on a long pole or collect them from freshly felled trees. Moreover, foliage of seedlings and small saplings often differs from that of mature trees, and spring and summer growth flushes on the same branch often appear markedly different. This seasonal variation has been noted for many oaks, including laurel, post, blackjack, and especially water oak. For example, by late March or April, water oak leaves reach their normal size and shape—obovate with a wavy apex; the second flush of growth, which starts in late April or May, produces lobed leaves.

Identification is further complicated because hybrids commonly occur among the oaks.

The oaks are divided into two main groups: the white oaks and the red (or black) oaks. The white oaks have leaves with rounded lobes and no bristles; acorns mature the first fall, and the inner surfaces of their shells are glabrous. White oak, chestnut oak, and post oak belong to this group. The red oak group is characterized by bristle-tipped leaf lobes in such species as Shumard, southern red, northern red, cherrybark, and black oak. The red oak group also includes non-lobed species such as water, laurel, and willow oak, which usually have entire margins. Blackjack oak leaves usually lack lobes and bristles, but leaves with terminal lobes occasionally occur and may have one bristle per lobe. Acorns of the red oak group mature the second fall, and the inner surfaces of their shells are pubescent.

Southern red oak and its variety **cherrybark oak**, have almost identical acorns, but they can be distinguished by other characteristics. The leaf base of southern red oak is somewhat bell-shaped, but that of cherrybark is not. Southern red oak forms heavy ridges of bark; cherrybark does not.

The distinctive feature of **black oak** is its yellow-orange inner bark. Its leaves take three forms. Seedlings to small saplings have a "bear paw" leaf with only a suggestion of lobing. Lower leaves on large trees also have little lobing, but leaves from the middle and upper crown are clearly lobed. The uppermost leaves, which have seven lobes and deep sinuses, are usually illustrated as typical.

Scarlet, **northern red**, and **Shumard oak**, are difficult to distinguish. Northern red oak leaves have shallow sinuses and a dull-green upper surface with little or no pubescence in the vein axils on the underside. Shumard oak leaves have a glossier surface, shallow to deep sinuses that are usually wider than the adjacent lobes, and definite hairiness at the vein axils. The sinuses of scarlet oak are usually wider than their adjacent lobes, which are usually toothed. Both Shumard and scarlet oak have outstanding fall coloration.

Blackjack oak can be recognized by its leathery, usually entire, broadly obovate leaf, which has a rusty undersurface. The branches are stout, irregular, gnarled, drooping to horizontal.

Laurel oak and **water oak** are similar in size and shape, but water oak has oblong-obovate or spatula-shaped leaves gradually narrowed to a wedge-shaped base. Laurel oak leaves are elliptic to oblong-ovate. Laurel oaks tend to shed leaves late and thus may retain about 30 to 50 percent of their lower leaves after water oaks are bare. Some recent authors separate the laurel oaks into two species, upland laurel oak, *Q. hemisphaerica* Bartr., and swamp laurel oak, *Q. laurifolia* Michx.

White oak has a thin, light green leaf with a light glaucous bloom at maturity; it is oblong or ovate, with rounded lobes and three to five narrow sinuses extending nearly to the mid-rib. The cup scales of the acorn-cup are heavy and distinct.

Post oak has stout, irregular branches. The leathery leaves are usually five-lobed; usually the two side lobes are at right angles to the central axis, thus forming a cross-shaped leaf.

Chestnut oak resembles swamp chestnut oak, *Q. michauxii* Nutt., a commercially important tree southwide. Chestnut oak is primarily a northeastern tree, extending into the South along the Appalachian highlands into northern Georgia and Alabama where its range overlaps that of swamp chestnut oak, and its leaves lack the dense pubescence found on those of swamp chestnut oak.

Common elms include **American elm** and **winged elm**. Both bloom after a freeze breaks dormancy. For example, if a killing frost occurs in the last week of November or the first week of December, American elm will bloom the first week of January. If no killing frost occurs by December, American elm may not bloom until the third week of January. Winged elm usually blooms 10 days to 2 weeks later than American elm. Small winged elm trees frequently have a corky outgrowth on opposite sides of twigs at least 3 years old. Mature trees often lack this characteristic. The American elm leaf has an oblique base and its fruits are pubescent or ciliate samaras about 12 mm in diameter; winged elm has a smaller leaf with roung to acute leaf bases and a very ciliate samara about 8 mm long.

Young **sugarberry** and **hackberry** trees are readily recognized by a whitish to light gray bark dotted with small corky warts. Older trees often have relatively smooth, light to medium gray bark. Leaf margins of sugarberry are usually entire or indistinctly toothed; the upper half of hackberry leaves are usually conspicuously serrate. Both species produce tiny flowers on the new growth when the leaves are about half normal size. The fruit of sugarberry is orange-red to black; that of hackberry is dark red to nearly black at maturity.

Yellow-poplar has alternate, 4- to 6-lobed leaves with truncate to distinctly notched apices, a unique feature among American trees. The flowers are tulip-like with red markings on a greenish-yellow background. The fruit is a cone-like aggregate of samaras.

Sweetbay produces moderate-sized trunks on uplands or numerous pole-like suckers in branch bottoms. It is evergreen in the southern part of its range and deciduous in the northern portion. A wind blowing in the crown will expose the silvery underside of the leaves. The white flowers, about 5 to 10 cm in diameter, open for the first time about 3 P.M. and close about 9 P.M. They reopen the next morning and shed their stamens. The fruit is a green pickle-like aggregate of follicles that splits open to reveal red seeds. Sweetbay and yellow-poplar, both members of the Magnolia family, have stipule scars circling the twigs.

Sweetgum is easily recognized by its alternate, star-shaped, palmately lobed leaves. Some trees have corky outgrowths on the small branches. Its flower consists of several round clusters of stamens arranged in a raceme and a stalked pistillate head that develops into spiny, woody fruit containing many seeds.

Red maple has simple, opposite leaves that are usually glaucous and pubescent. The flowers appear in early February and the fruit is a double samara. The variety *A. rubrum* var. *drummondii* (Hook. and Arn.) Sarg., which has densely matted white hairs on the undersides of young leaves, grows in swamps throughout the South. Leaves may have three to five lobes, but southern trees are predominantly three-lobed. For this reason, some authors recognize the southern form as *A. rubrum* var. *tridens* Woods.

The leaves of **black tupelo** are alternate, elliptical to obovate, and become spotted early in their development, turning purplish in September before their early shedding. The flowers are small, inconspicuous, and produce a blue-black fruit.

Two of the most common ashes are **white ash** and **green ash**. The most reliable distinction between the two species appears to be samara differences. White ash has a plump, short seed end with the wing practically terminal, whereas green ash has a slender seed end and the wing extends more than halfway down the seed end. White ash usually has a rounded leaflet base, but green ash has wedge-shaped leaflet bases. The undersurfaces of fresh white ash leaves are white, but the color is difficult to detect on dry specimens. Green ash leaves are green on both surfaces, although somewhat paler on undersurfaces.

KEY TO THE HARDWOODS

The key is composed of paired statements (couplets), one true and one false for any given specimen. The guide numbers at the end of statements are used to locate the next couplet. Follow the true statements until you come to a common name. If you have made no mistake in interpreting the paired statements, you should arrive at the correct identity of the specimen. Then check the text and illustration; illustrations are arranged alphabetically by common name.

1. Leaves compound, with blades divided into leaflets 2
1. Leaves simple, blades not divided into leaflets 7
    2. Leaves with opposite arrangement on twigs 3
    2. Leaves with alternate arrangement on twigs 4
3. Leaflets with rounded bases, conspicuously whitish below when fresh; seed end of samara thickened, wing terminal only . . . . **white ash** (fig. 3-34)
3. Leaflets with wedge-shaped bases,green below; wing terminal and extending about half the length of the seed . . . . **green ash** (fig. 3-33)
    4. Buds valvate; buds, fruits, and lower surface of leaflets covered with yellow glandular scales; fruit winged on upper half of husk suture, husk thin, shell thin, meat bitter **bitternut hickory** (fig. 3-37)
    4. Buds imbricate, composed of overlapping scales 5
5. Leaflets typically 5, glabrous except for a few hairs on rachis and midribs; bark shaggy . **shagbark hickory** (fig. 3-40)
5. Leaflets 7 6
    6. Leaflets densely tomentose; bark tight, in diamond-shaped pattern; husk very thick, shell thick, meat sweet . . . . **mockernut hickory** (fig. 3-38)
    6. Leaflets usually glabrous; bark tight, in diamond-shaped pattern; husk moderately thick, shell thick, meat sweet, husk tardily dehiscent . . . . **pignut hickory** (fig. 3-39)

7. Leaves essentially evergreen, large percentage staying on trees until bud expansion, dark green above, silky white pubescent below; flowers white, about 5 to 8 cm in diameter. . **sweetbay** (fig. 3-55)

7. Leaves typically deciduous, or trees retaining some dead leaves to bud expansion 8

  8. Leaf margins entire 9

  8. Leaf margins lobed or toothed 12

9. Leaves with rusty pubescence below, broadly obovate, leathery bases tapering to cordate or cuneate . . . . . . **blackjack oak** (fig. 3-43)

9. Leaves essentially glabrous or with a few hairs in vein axils 10

  10. Leaves shiny below, elliptic or rhombic to spatulate **laurel oak** . . . . . . (fig.3-46)

  10. Leaves dull green below 11

11. Leaves elliptic to obovate, strongly veined with purple spots and discoloration in summer; fruit a drupe . . . . . . **black tupelo** (fig. 3-57)

11. Leaves abruptly obovate, bases wedge-shaped, few lateral veins; fruit an acorn **water oak** (fig. 3-52)

  12. Leaf margins toothed 13

  12. Leaf margins lobed 16

13. Margins distinctly toothed, blades narrowly to broadly ovate, base unequal, apex long acuminate . . . . . . **sugarberry** (fig. 3-54)

13. Margins indistinctly toothed 14

  14. Teeth obtuse or rounded, leaf base wedge shaped, stellate pubescent below. . . **chestnut oak** (fig. 3-45)

  14. Teeth sharp 15

15. Leaves normally elliptic, veins prominent below, bases rounded; corky outgrowths on older branches, often lacking on large trees . . . . . . **winged elm** (fig. 3-36)

15. Leaves broadly oval, pinnate veins distinct, margins doubly toothed, bases oblique, unequally rounded . . . . . . **American elm** (fig. 3-35)

  16. Leaves palmately lobed 17

  16. Leaves pinnately or apically lobed 18

17. Leaves opposite, more or less glaucous and pubescent below; fruit a double samara . **red maple** (fig. 3-41)

17. Leaves alternate, glabrous below; fruit spherical, woody with spine-like projections; corky outgrowths on branches frequent . . . . . . **sweetgum** (fig. 3-56)

  18. Blades truncate to notched at apex, 4-lobed; fruit an aggregate of samaras; flower conspicuous, greenish-yellow with red markings . . . . . . **yellow-poplar** (fig. 3-58)

  18. Blades with acute to obtuse apices 19

19. Blades apically 3-lobed 20

19. Blades pinnately lobed 21

  20. Blades broadly obovate, base rounded, rusty pubescent below **blackjack oak**. . (fig. 3-43)

  20. Blades narrowly obovate, base wedge-shaped, mostly glabrous. . **water oak**. . . (fig. 3-52)

21. Leaves with rounded lobes 22

21. Leaves with bristle tips to lobes and lateral teeth 23

  22. Leaves with 7 to 9 lobes, divided nearly to the midrib, whitish below **white oak** (fig. 3-53)

  22. Leaves with 5 unequal lobes, upper lateral pair larger, squarish, at right angles to midrib, crosslike in appearance, pubescent below . . . . . . **post oak** (fig. 3-48)

23. Leaves pubescent below, whitish to tawny 24

23. Leaves glabrous below or with a few hairs on midrib and in vein axils 26

  24. Leaves with 7 to 9 lobes, terminal lobes long, strap-shaped, slightly curved, bases bell-shaped . . . . . . **southern red oak** (fig. 3-51)

  24. Leaves with 7 to 11 lobes 25

25. Leaves oblong, 7 to 11 lobes, base broadly wedge-shaped to truncate, secondary lobes are rare; inner bark reddish . . . . . . **cherrybark oak** (fig. 3-44)

25. Leaves broadly oval, 7 to 9 lobes, each lobe with secondary bristle tipped teeth; inner bark yellow-orange . . . . . . **black oak** (fig. 3-42)

  26. Upper leaf surface glossy green 27

26. Upper leaf surface dull green, 7 to 9 lobes, 8 to 22 cm long, round sinuses extending less than halfway to midrib. . . . . **northern red oak** (fig. 3-47)

27. Leaves with 7 to 9 narrow lobes, sinuses extending more than halfway to midrib. . . **scarlet oak** (fig. 3-49)

27. Leaves with 5 to 7 narrow lobes, rounded sinuses, extending about three fourths of way to midrib . . . . **Shumard oak** (fig. 3-50)

Readers desiring additional information on the identification of southern hardwood species should find the following references useful:

Bailey 1949
Brown 1945
Collingwood and Brush 1974
Correll and Johnston 1970
Fernald 1950
Harlow 1959
Harlow and Harrar 1941
Harrar and Harrar 1962
Little 1953
Muller 1951
Preston 1970
Sargent 1961
Small 1933
Vines 1960
Wharton and Barbour 1973

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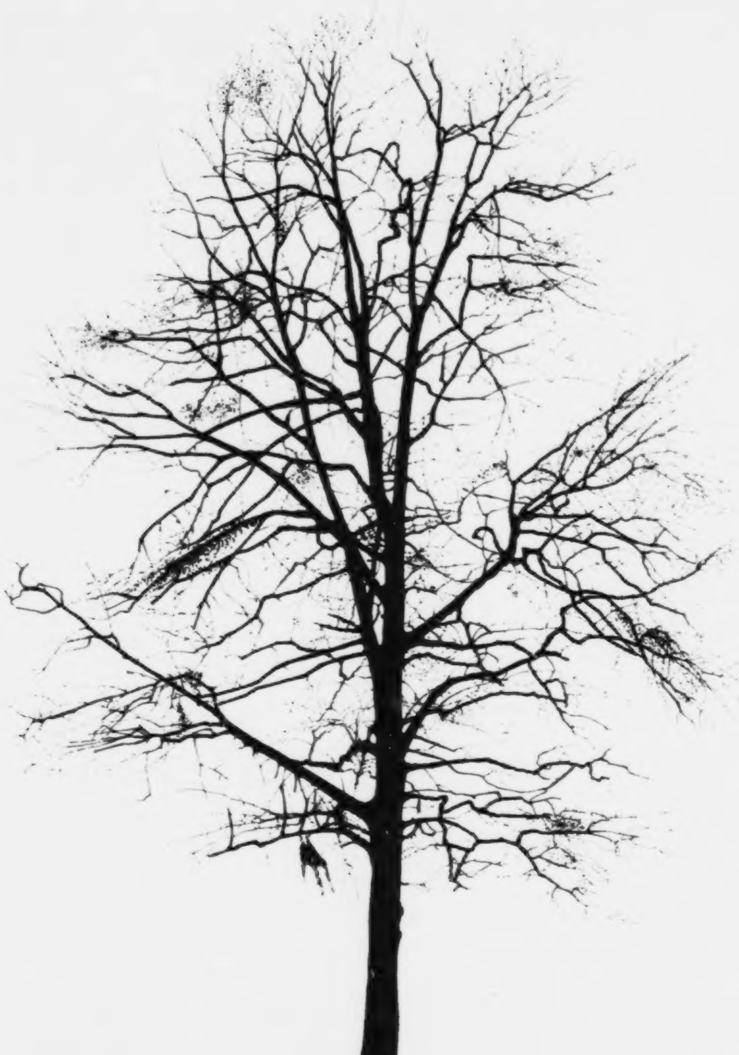
GREEN ASH



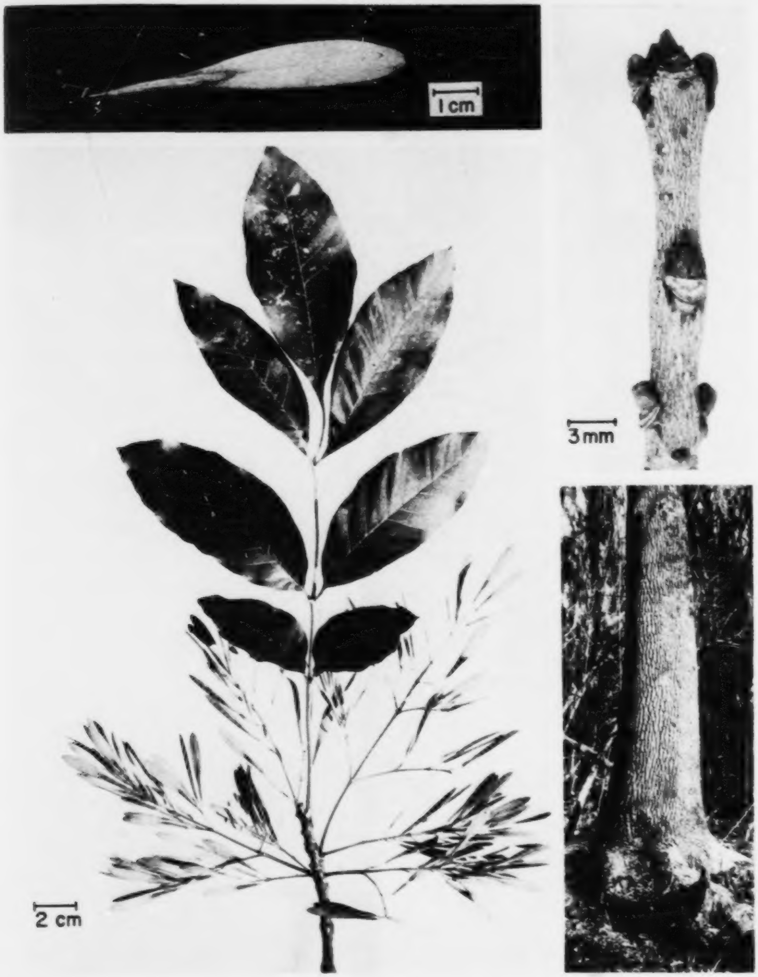
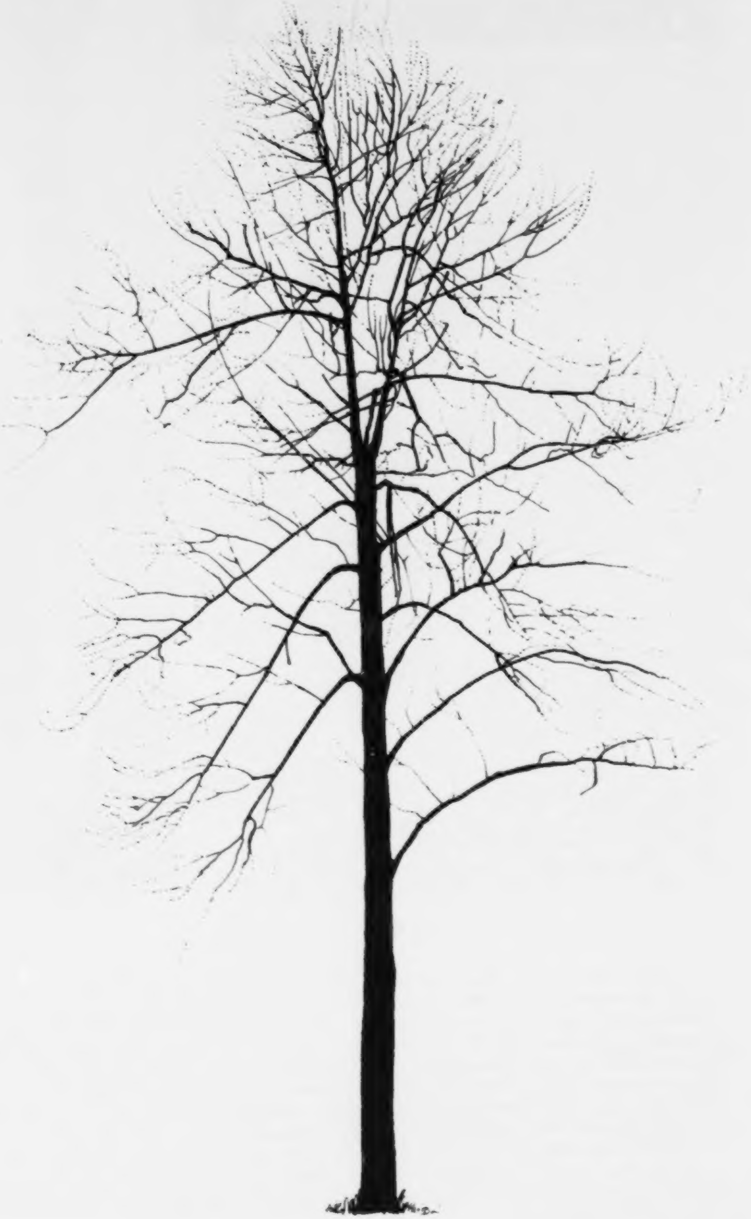


Figure 3-33.—Ash, green (*Fraxinus pennsylvanica* Marsh.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK brownish, smooth when young, then breaking into narrow ridges with shallow narrow furrows. BRANCHES drooping to spreading and ascending. TWIGS stout, 4 to 6 mm in diameter, olive green. BUDS: terminal black; smaller lateral buds tightly appressed to the generally straight upper edge of the leaf scar. LEAVES opposite, deciduous, odd-pinnately compound with 5 to 7, occasionally 9, leaflets; leaflets narrowly to broadly elliptical, apex acuminate, margin entire to finely serrate, base wedge-shaped, hairy below along the veins. FLOWERS unisexual (plants dioecious); pistillate inconspicuous in open panicles; staminate in compact conspicuous clusters. FRUIT a samara 25 to 50 mm long, seed end conspicuously slender and extending about half the length of the samara, wing decurrent on seed end.

WHITE ASH



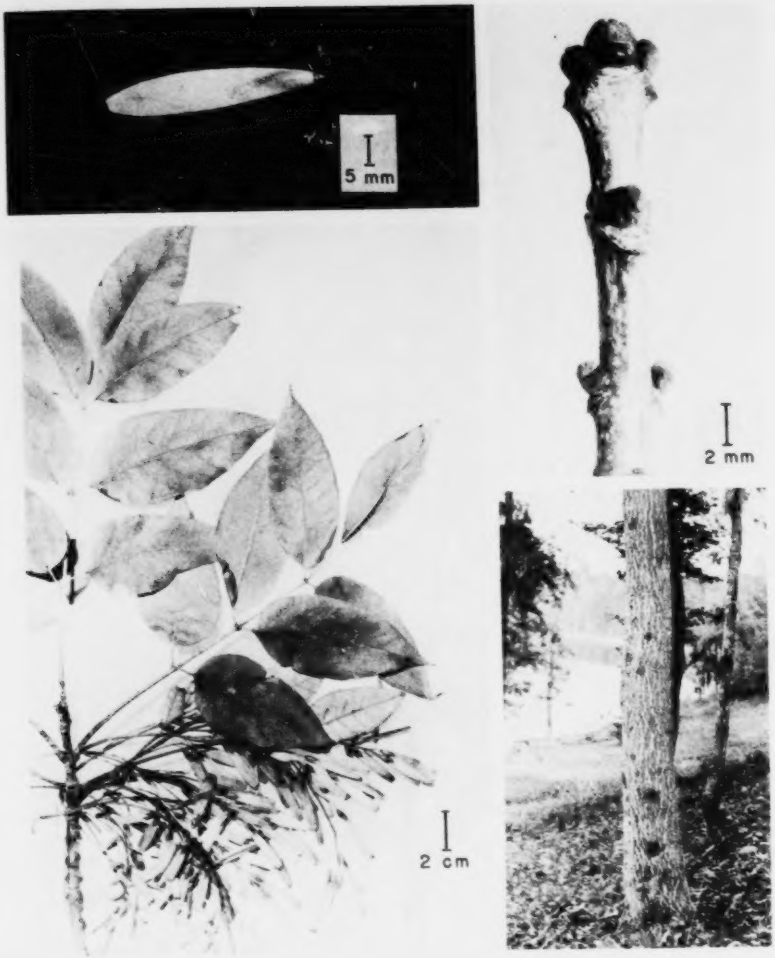
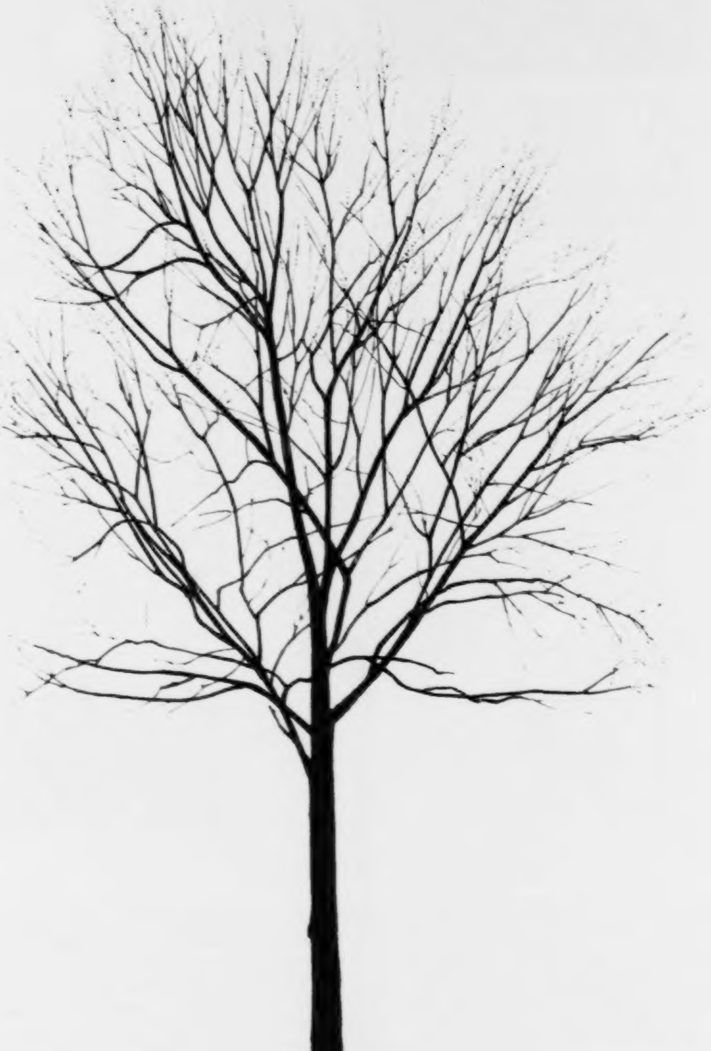


Figure 3-34.—Ash, White (*Fraxinus americana* L.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK gray to brownish, divided into narrow, deep furrows and ridges of equal width. BRANCHES stout, wide-spreading. TWIGS 3 to 6 mm in diameter. BUDS (terminal) broadly ovoid consisting of 4 appressed scales, dark brown to black; lateral buds spherical, tightly appressed to a crescent-shaped leaf scar. LEAVES opposite, deciduous, odd-pinnately compound; 20 to 30 cm long, white below when fresh; leaflets 7 to 9, petiolulate, oval to ovate, 5 to 15 cm long, 3 to 5 cm wide, apex acuminate, margin essentially entire, base broadly rounded, pinnate veins conspicuous on underside. FLOWERS unisexual (plants dioecious); pistillate inconspicuous about 1 mm in diameter, arranged in dense paniculate clusters; staminate conspicuous in mass. FRUIT a samara, 25 to 60 mm long, wing terminal on the thickened seed.

AMERICAN ELM



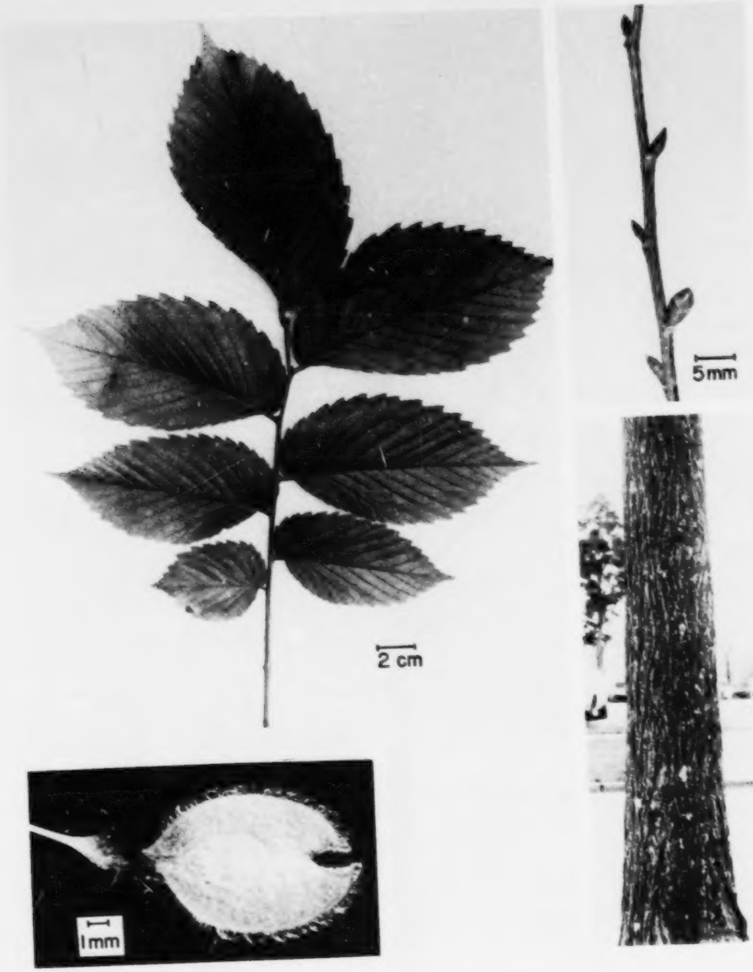
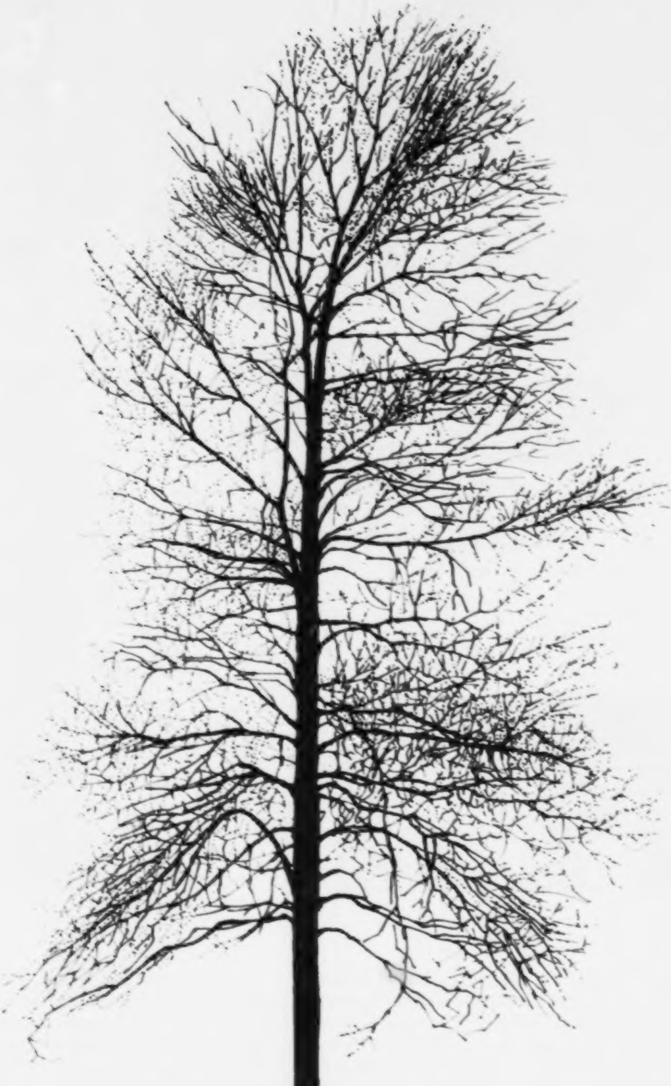


Figure 3-35.—Elm, American (*Ulmus americana* L.) (Left) Winter silhouette. (Right) Botanical details. (Description) **BARK** gray to blackish, thick, divided into flat ridges by deep furrows. **BRANCHES** ascending, arching, and spreading; open-grown trees vase-shaped in outline. **TWIGS** 2 to 3 mm in diameter with 5 to 7 leaves which increase in size from basal to apical leaf, red-brown. **BUDS** (leaf) brown, small, scaly, acute. **LEAVES** alternate, deciduous, simple; broadly ovate, 5 to 15 cm long, 4 to 6 cm wide; apex acuminate, margin usually doubly serrate, base oblique on short petiole; upper surface smooth, marked with sunken veins pinnately arranged; veins more prominent on underside. **FLOWER** perfect, buds greatly enlarge before opening; with very small flowers abundant in clusters; opening before the leaves expand, blooming from late December into February. **FRUIT** a samara, oval to circular with wing surrounding the seed, about 10 mm in diameter, margin ciliate.

WINGED ELM



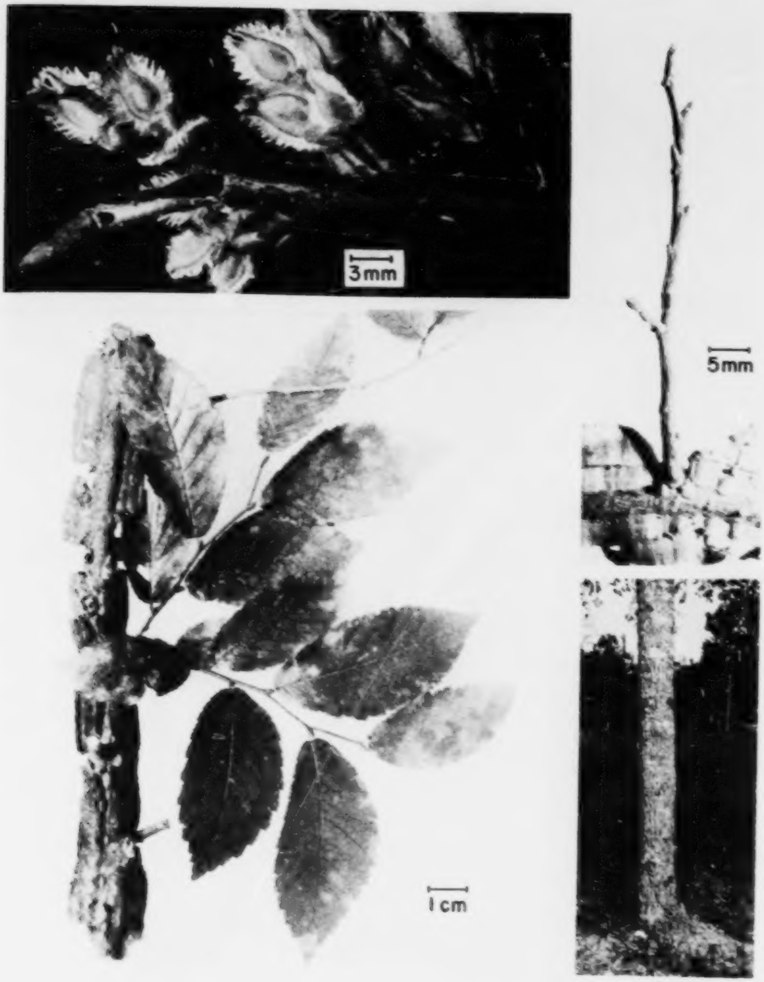


Figure 3-36.—Elm, winged (*Ulmus alata* Michx.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK dark, smooth at first becoming deeply furrowed on larger trees. BRANCHES slender, ascending to spreading, corky ridges or wings on branches 3 years or older. TWIGS about 2 mm in diameter, light green tinged with red. BUDS sharp-pointed, divergent from twig 3 to 4 mm long. LEAVES alternate, deciduous, simple; broadly ovate to elliptic, 4 to 8 cm long, 2 to 4 cm wide; apex acute to short-acuminate, margin doubly to triply serrate, base rounded; dull green above, lighter green below with prominent pinnate veins. FLOWERS perfect, abundant, tiny, opening just before leaves unfold, several in a cluster at a leaf scar, blooming late January into February. FRUIT a samara, flat and elliptic, 6 to 8 mm long, margin ciliate.

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BITTERNUT HICKORY

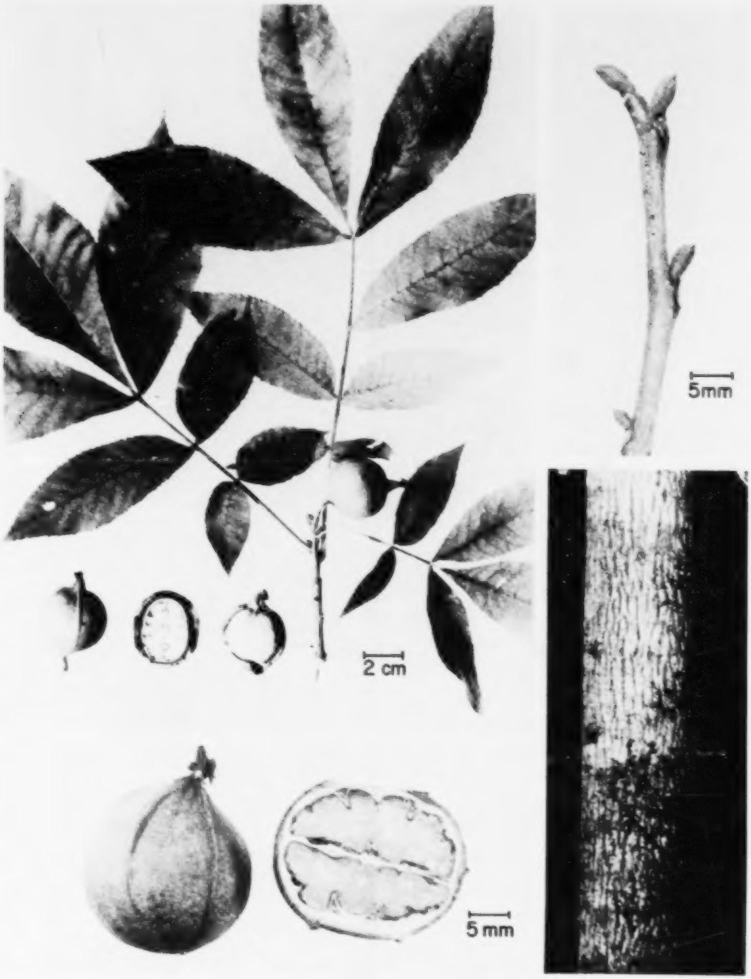
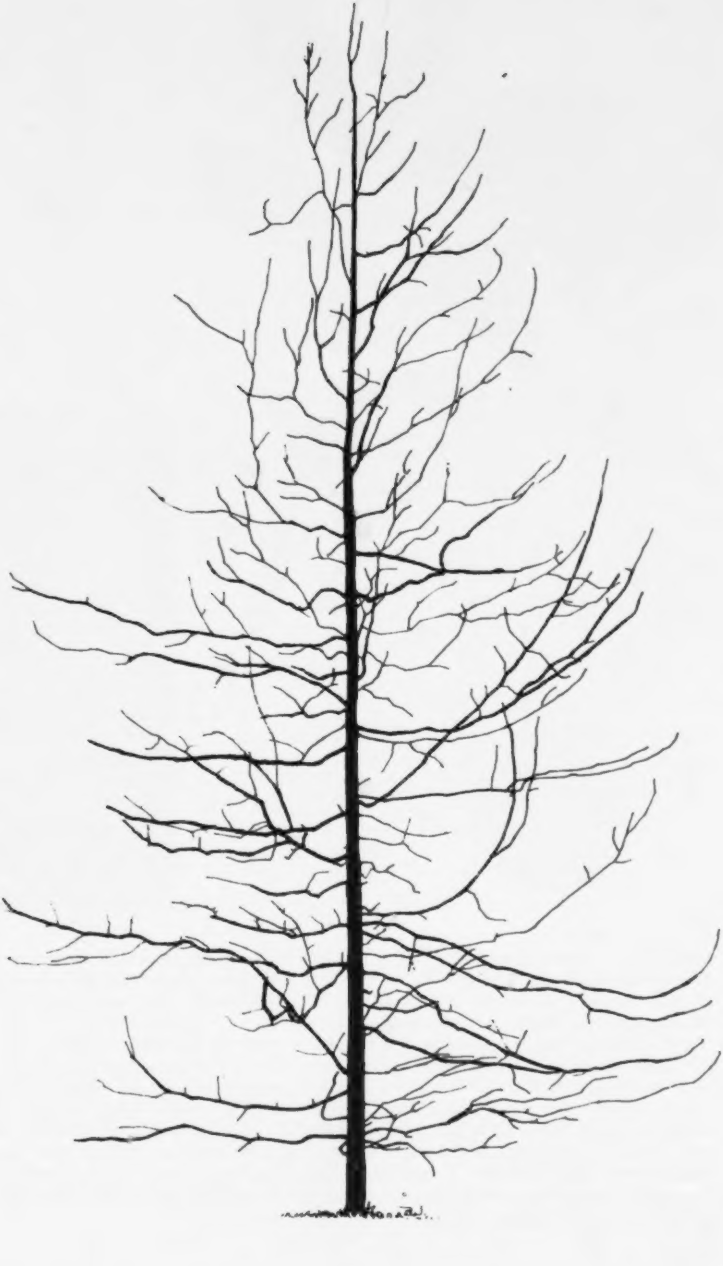


Figure 3-37.—Hickory, bitternut (*Carya cordiformis* (Wangenh.) K. Koch). (Facing page) Botanical details. (Description) BARK brown to slate gray, smooth to lightly furrowed or with strongly interlaced ridges. BRANCHES stiff, ascending, spreading. TWIGS slender, glossy, often with yellow glands early in the season. BUDS compressed, ovoid, 6 to 10 mm long, covered with yellow, valvate glandular scales. LEAVES alternate, deciduous, odd-pinnately compound, 15 to 25 cm long with 7 to 9 leaflets 7 to 15 cm long 3 to 6 cm wide; lateral leaflets narrowly to broadly elliptic, terminal leaflet largest and usually obovate, apex acuminate, margin finely serrate, base wedge-shaped, with yellow glands on undersurfaces and on rachis. FLOWERS unisexual, staminate in 3-branched catkins appearing after leaves; pistillate terminal on new growth. FRUIT ovate to subglobose, 2 to 3 cm in diameter, often slightly compressed, 4-winged on sutures from apex to middle of husk, husk thin, covered with yellow glandular scales, shell of nut thin, meat very bitter.

MOCKERNUT HICKORY



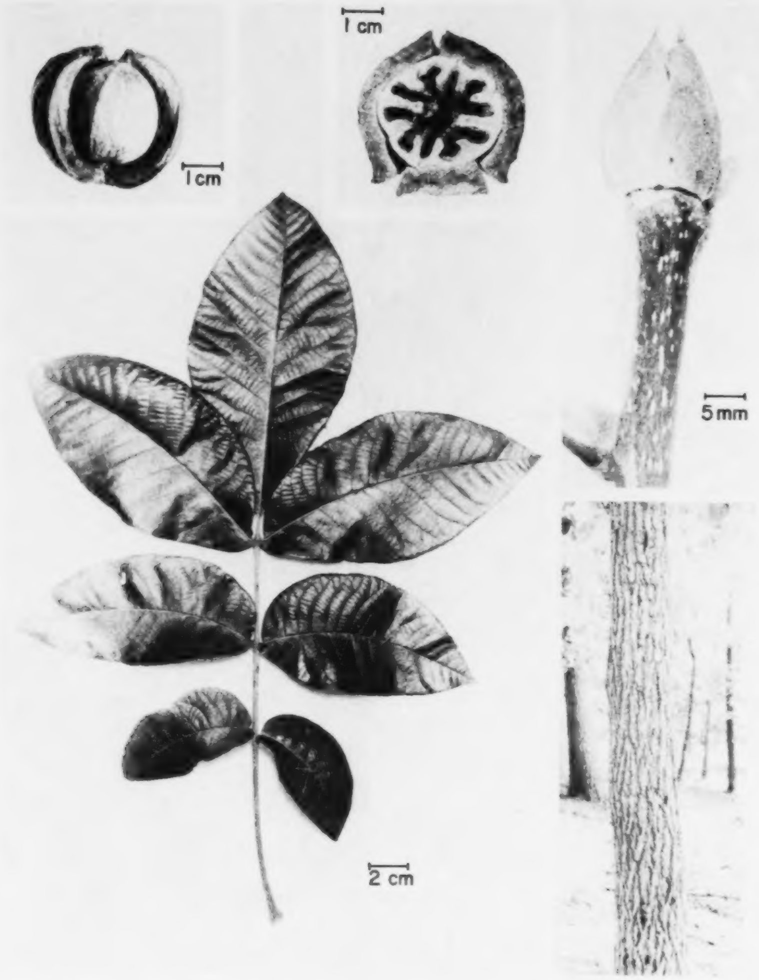
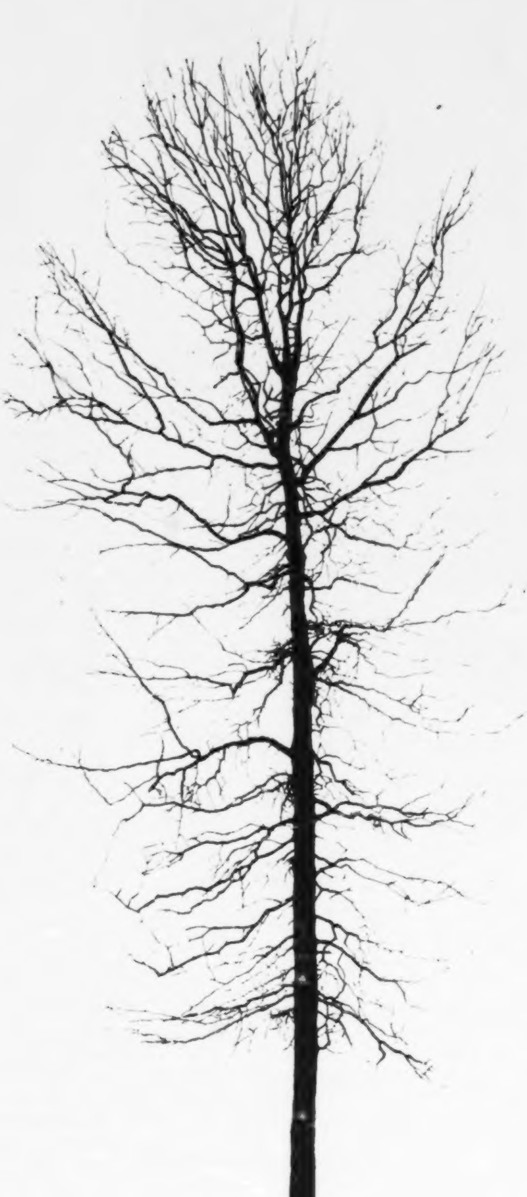


Figure 3-38.—Hickory, mockernut (*Carya tomentosa* Nutt.). (Left) Winter Silhouette. (Right) Botanical details. (Description) BARK grayish, tight, marked with distinct diamond-shaped ridges and furrows. BRANCHES stout, drooping to spreading and ascending. TWIGS 10 to 12 mm in diameter, conspicuous leaf scars. BUDS (terminal) 10 to 15 mm long, 5 to 8 mm in diameter, scales imbricate. LEAVES alternate, deciduous, odd-pinnately compound, 20 to 40 cm long with 5 to 7 drooping leaflets; yellow hairs and glandular hairs on lower leaflet surface, apex acuminate, margin finely serrate, base obtuse, on very short petiolules. FLOWERS unisexual, appearing in spring with developing leaves, staminate in 3-parted drooping catkins, pistillate terminal on new growth. FRUIT subglobose to obovate, 3 to 5 cm in diameter, husk 1 cm thick, slow to open, shell of nut thick and hard, meat sweet.

PIGNUT HICKORY



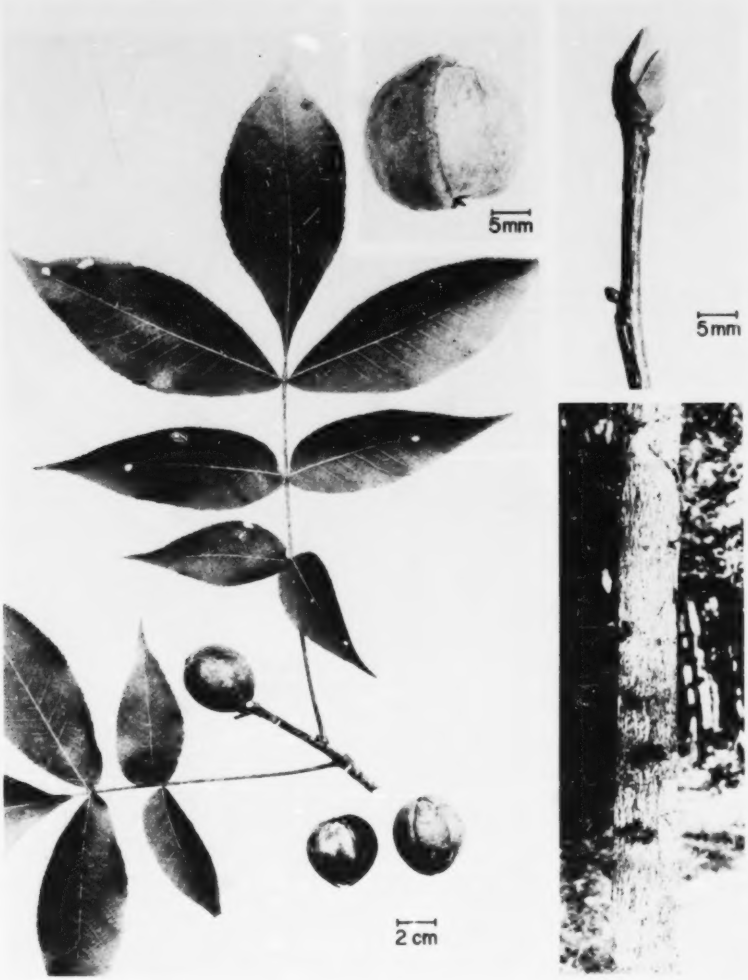


Figure 3-39.—Hickory, pignut (*Carya glabra* (Mill.) Sweet). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK light to dark gray, often blackish, rough and deeply furrowed. BRANCHES stout, drooping to spreading. TWIGS 3 to 5 mm in diameter, reddish brown, smooth. BUDS ovoid, acute, glabrous, 8 to 12 mm long, scales imbricate. LEAVES alternate, deciduous, odd-pinnately compound, 20 to 40 cm long, usually with 7 leaflets; upper pair and terminal largest, 10 to 15 cm long by 4 to 6 cm wide, broadly oval to slightly obovate. FLOWERS unisexual, staminate in 3-branched catkins appearing about the time of leaf maturity; pistillate terminal on new growth. FRUIT oblong to obovoid to obpyriform, 30 mm in diameter by 35 mm long, husk about 3 mm thick, tardily dehiscent, shell of nut thick, meat sweet.

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SHAGBARK HICKORY

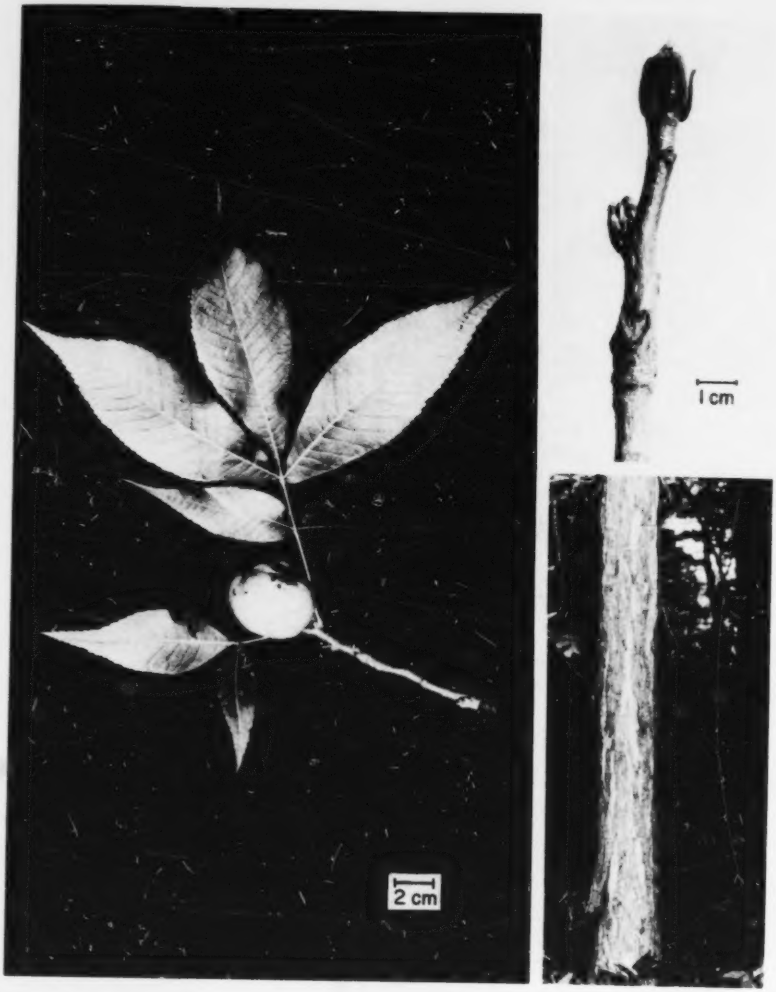
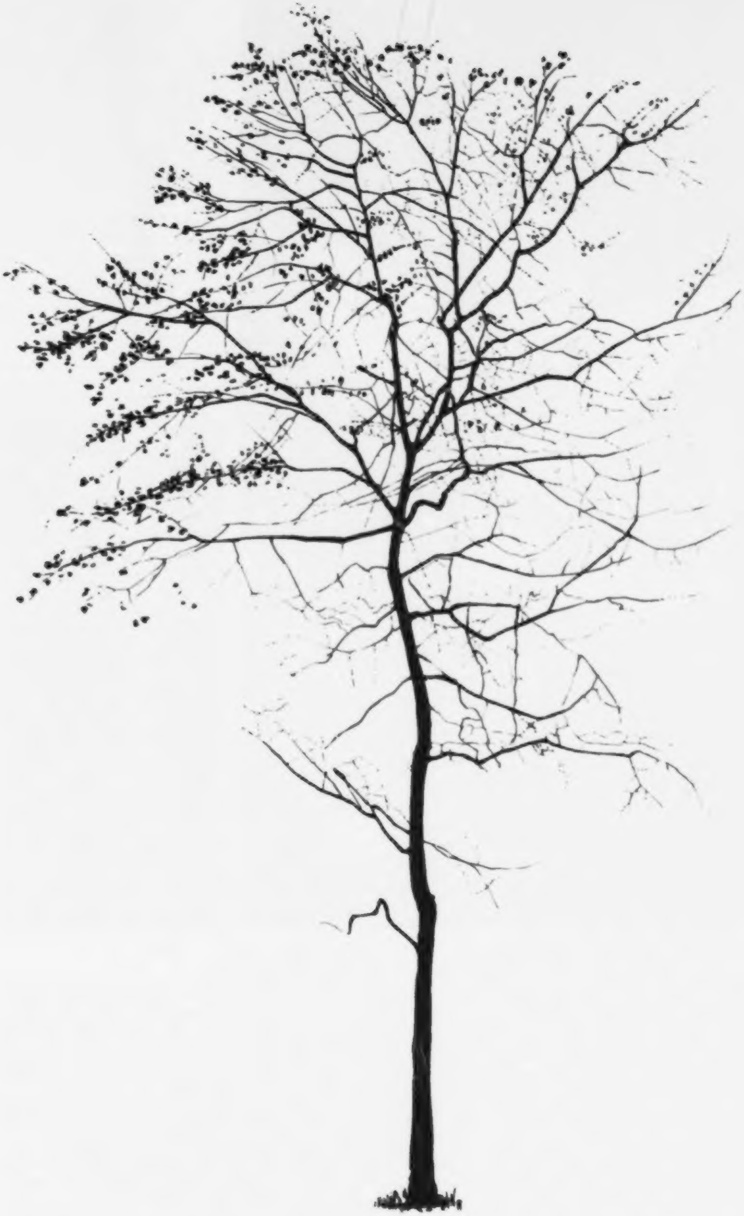


Figure 3-40.—Hickory, shagbark (*Carya ovata* (Mill.) K. Koch). (Facing page) Botanical details. (Description) BARK smooth at first, then breaking into long, flat, irregular gray strips, to 5 mm thick, usually attached at the apex, free at the base. BRANCHES stout, smooth, spreading to ascending. TWIGS stout, orange-brown, leaf scars large. BUDS (terminal), 10 to 20 mm long, 6 to 8 mm in diameter, scales imbricate. LEAVES alternate, deciduous, odd-pinnately compound with 5 to 7 leaflets, usually 5 to 18 cm wide and 20 to 35 cm long; lateral leaflets ovate to ovate-lanceolate, terminal leaflet usually obovate, apices acute to acuminate, margins finely serrate, bases wedge-shaped, more or less yellow, pubescent below, gradually becoming glabrous with age. FLOWERS unisexual, appearing in spring with the developing leaves, staminate in 3-lobed catkins, pistillate on new growth. FRUITS subglobose, 2.5 to 6 cm in diameter, husk 3 to 5 mm thick, shell of nut hard and moderately thin, meat sweet.

RED MAPLE



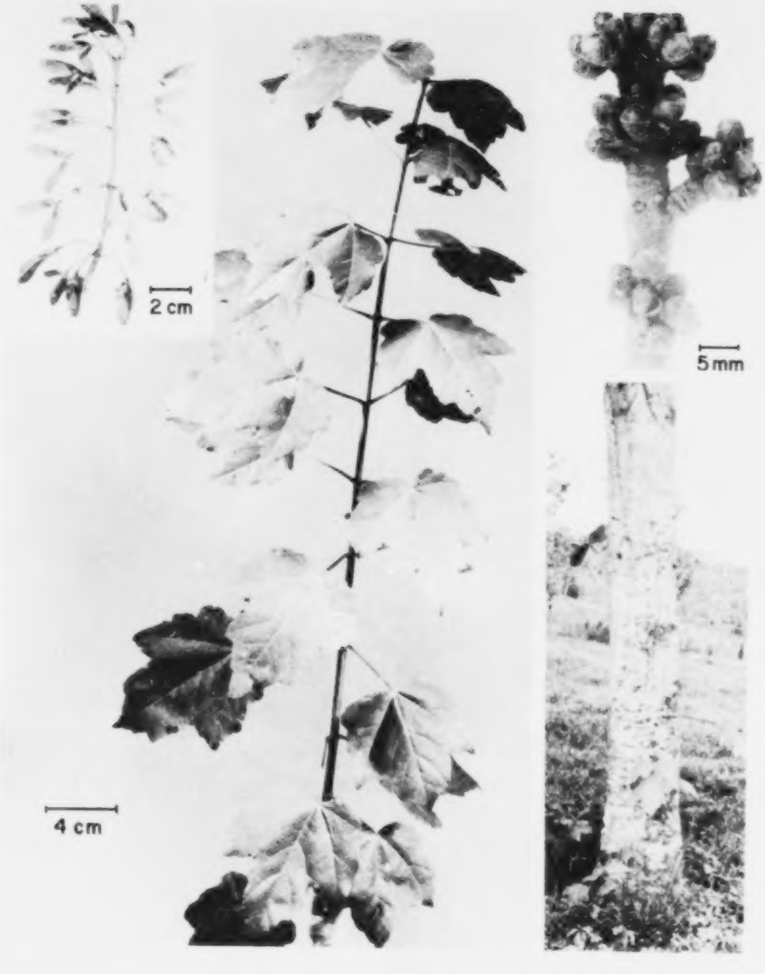
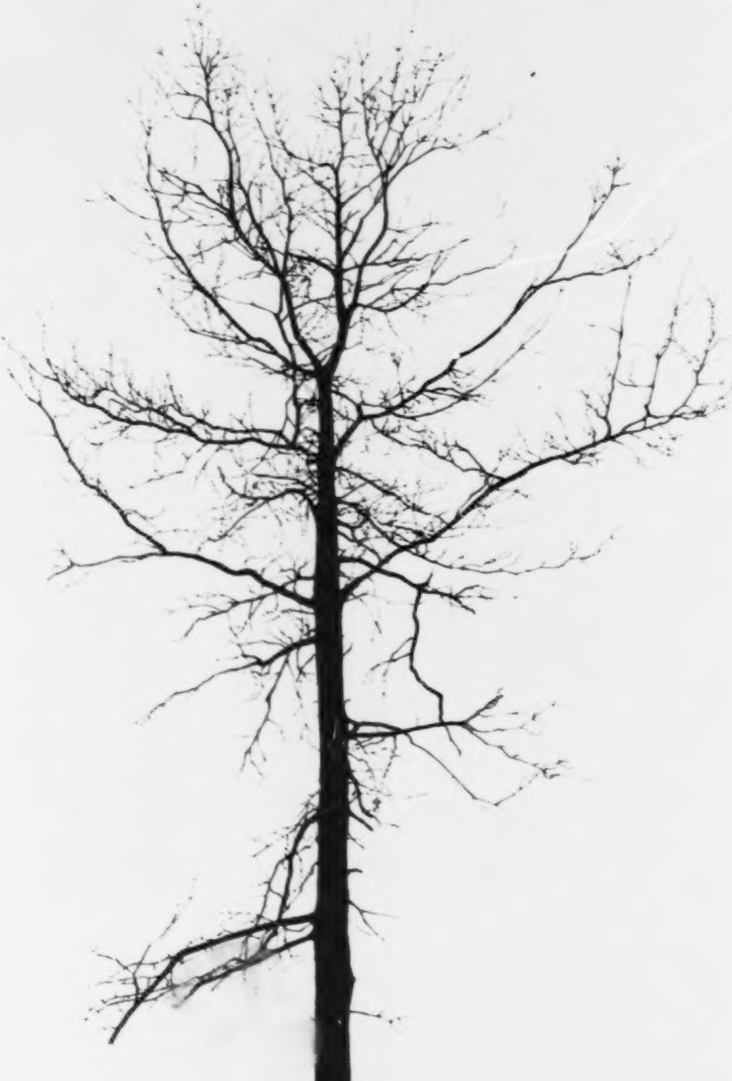


Figure 3-41.—Maple, red (*Acer rubrum* L.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK gray, divided into scaly ridges by narrow furrows. BRANCHES slender, spreading and ascending. TWIGS about 3 mm in diameter, reddish. BUDS spherical, reddish, clustered at apex of twig, scales with white ciliate margins. LEAVES opposite, deciduous, simple; ovate to almost circular, 4 to 9 cm long, 2-½ to 7 cm wide, usually longer than broad; 3-lobed near the apex, margin finely serrate; dark green above, glaucous and lightly pubescent below, pubescence usually shed. FLOWERS typically polygamous, occasionally with perfect flowers, small, forming dense clusters from separate buds before leaf expansion, conspicuous because of the red to orange coloration. FRUIT twin samaras 10 to 20 mm long.

Var. *drummondii:* LEAVES larger than typical red maple, usually broader than long; 3 to 5 lobes or occasionally scarcely lobed, margins coarsely toothed, conspicuously glaucous below, usually permanently tomentose. FRUIT samaras 4 to 5 cm long.

BLACK OAK



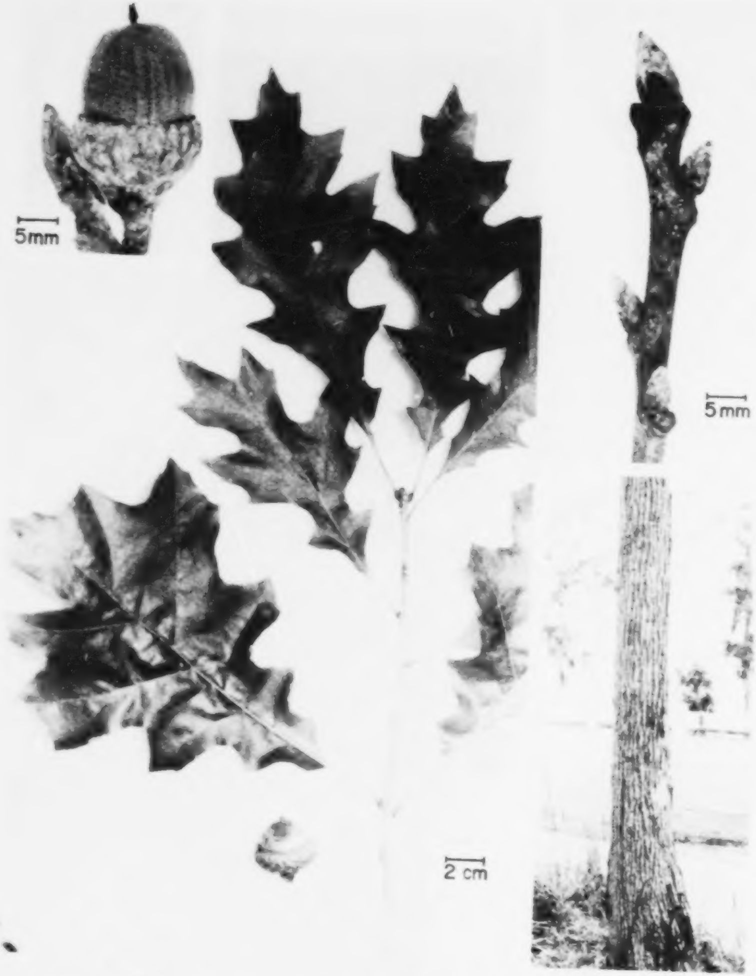
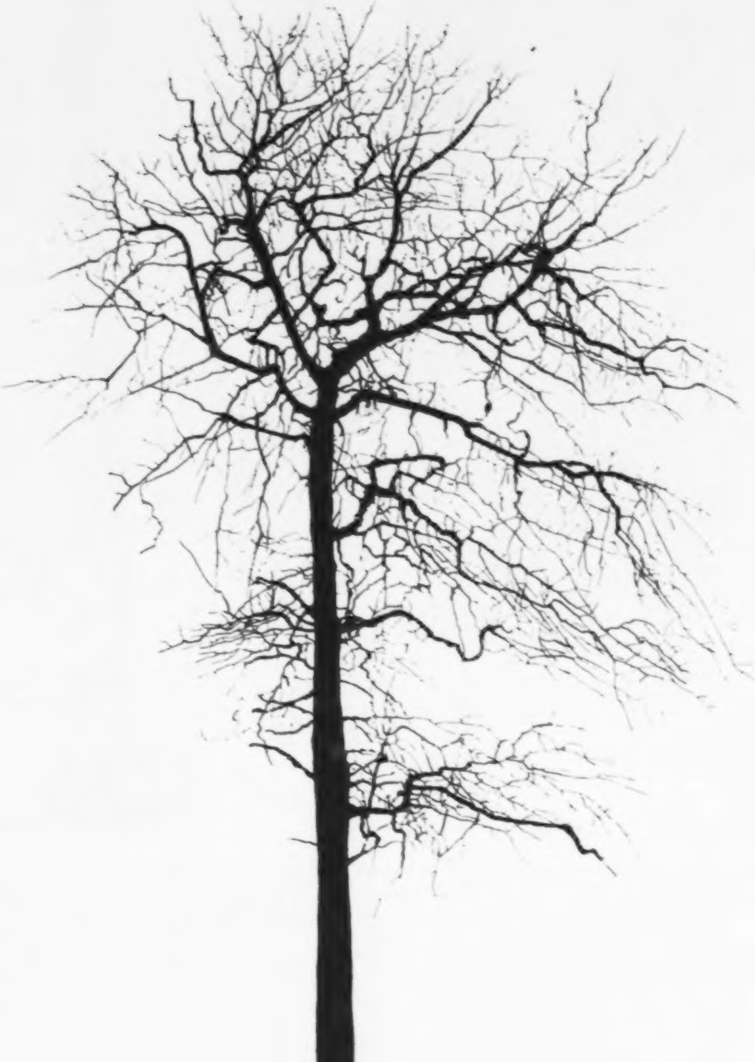


Figure 3-42.—Oak, black (*Quercus velutina* Lam.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK brownish-black on older trees, with thick, broad, scaly ridges and deep furrows; inner bark yellow-orange—the only American oak with this feature. BRANCHES stout, spreading to ascending. TWIGS about 5 mm in diameter, reddish brown to dark brown, lightly fluted. BUDS ovoid, 10 to 15 mm long, lateral buds sharply angled, scales ciliate, margin dark. LEAVES alternate, deciduous, simple; membranous in seedlings and saplings to somewhat leathery in the middle to upper crown; lower leaves broadly elliptic to obovate, 15 to 30 cm long, 10 to 15 cm wide, entire to faintly lobed; middle-crown leaves 10 to 20 cm long 10 to 15 cm wide, distinctly 5 to 9 lobed with broad, rounded sinuses, with apical bristles on each lobe; upper-crown leaves oblong to obovate, 8 to 20 cm long, 8 to 15 cm wide; dark shiny green above, yellow scurfy pubescence on young leaves of middle and upper crown, petioles 4 to 6 cm long, yellow to reddish. FLOWERS unisexual; staminate catkins 7 to 15 cm long; pistillate on short tomentose peduncles. FRUIT an oval to obovoid acorn, 10 to 25 mm long; cup cup-shaped to conical enclosing about ½ of the nut.

BLACKJACK OAK



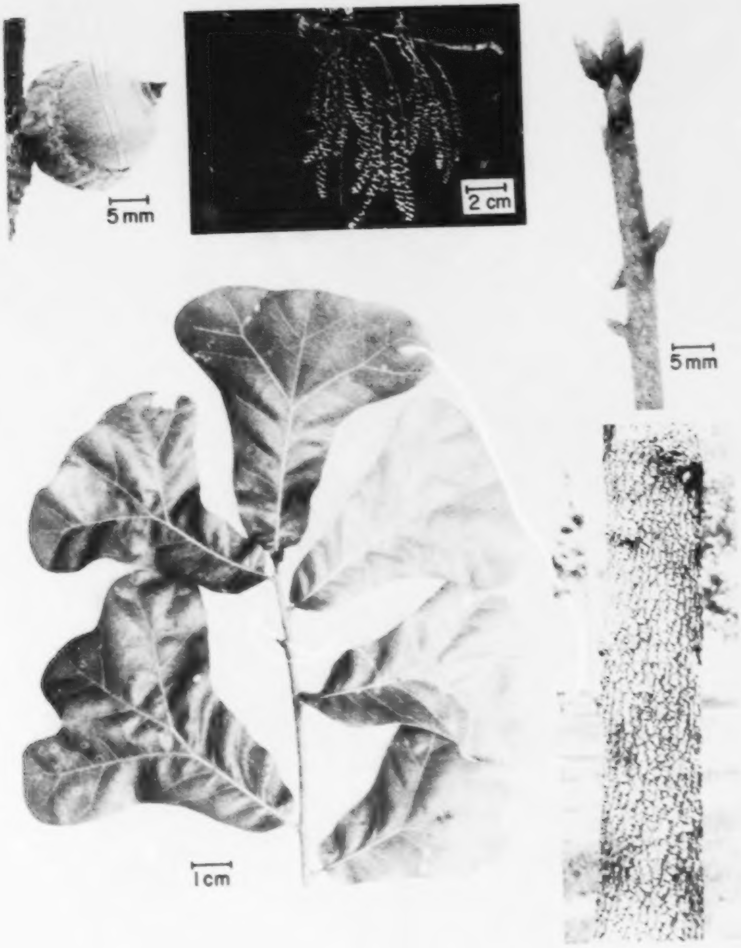
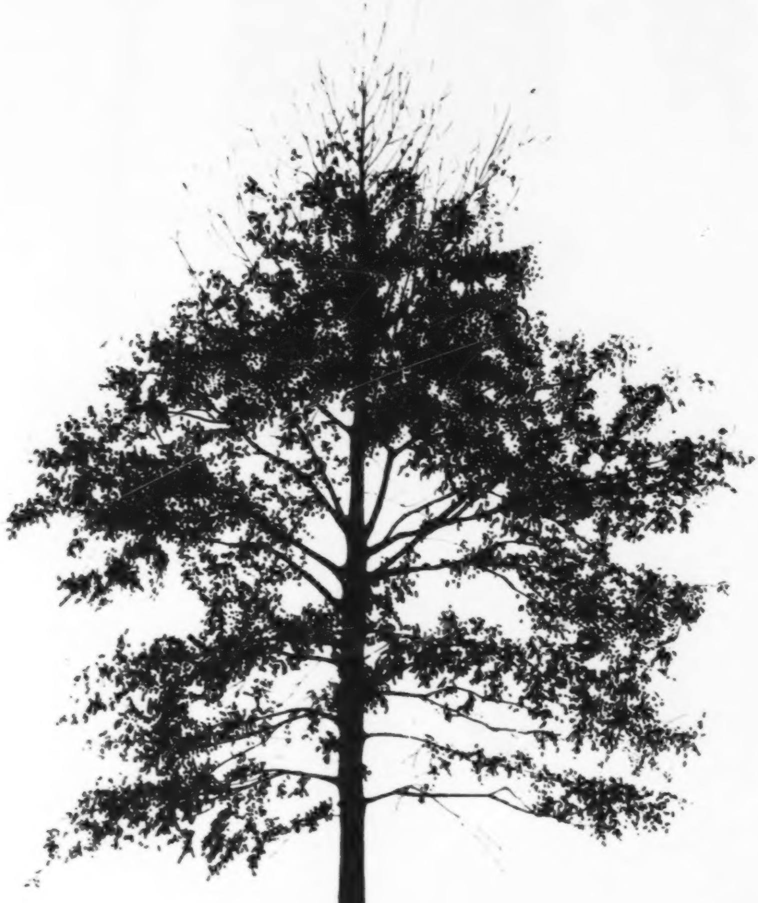


Figure 3-43.—Oak, blackjack (*Quercus marilandica* Muenchh.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK black, very rough, consisting of thick blocky plates. BRANCHES stout, spreading to drooping. TWIGS stout, about 5 mm in diameter. BUDS with rusty brown hairs, about 4 to 8 mm long. LEAVES alternate, tardily deciduous, simple, 7 to 25 cm long, broadly obovate at apex (bear-paw shape) tapering to a narrow base, margin entire or with 3 bristle-tipped apical lobes, upper surface dark green, rusty pubescent on undersurfaces. FLOWERS unisexual; staminate in catkins, appearing with the leaves; pistillate solitary or paired. FRUIT an acorn, cup enclosing ½ to ⅔ of the nut; nut nearly ovoid, 20 to 25 mm long by 15 to 20 mm in diameter.

CHERRYBARK OAK



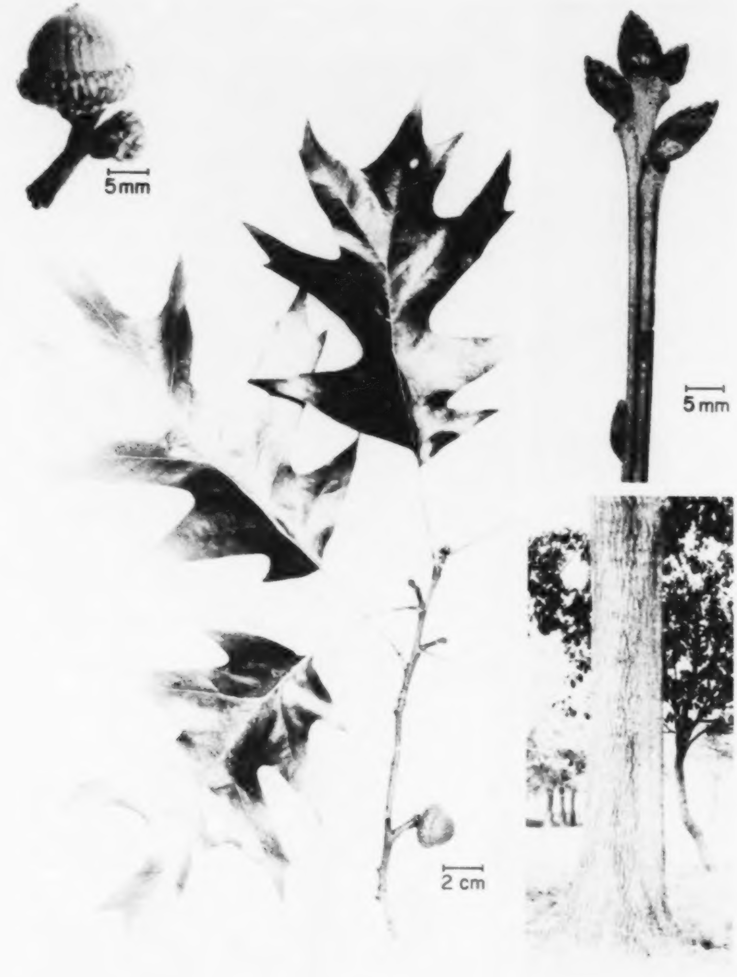
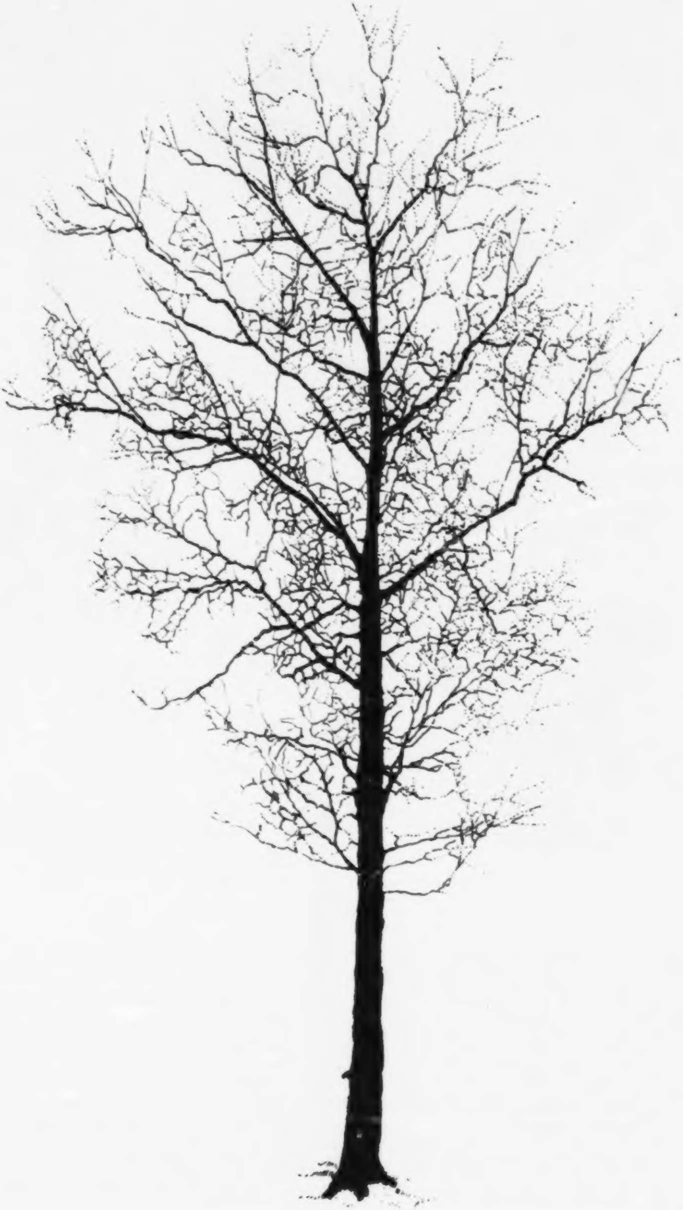


Figure 3-44.—Oak, cherrybark (*Quercus falcata* Michx. var. *pagodaefolia* Ell.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK dark gray to gray-black consisting of appressed scales in narrow flat ridges with shallow furrows. BRANCHES spreading to ascending, stout. TWIGS 2 to 4 mm in diameter, reddish, lightly fluted. BUDS ovoid, 10 to 15 mm long, angled, scales pubescent with dark margins. LEAVES alternate, tardily deciduous, persisting into December, simple, oval to oblong, 12 to 20 cm long, 7 to 8 cm wide; with 5 to 11 lobes, major lobes opposite each other, large rounded sinuses extending nearly to the midrib, margin entire with occasional bristle-tipped teeth near the apex of the lobes, dark green above, permanently pubescent below, sometimes thinly so, varying from white to rust color, especially on drying. FLOWERS as in *Q. falcata*. FRUIT an acorn broader than tall; cups 12 to 15 mm wide; nut about 8 to 10 mm long, subglobose, flattened at base, rounded at apex.

CHESTNUT OAK



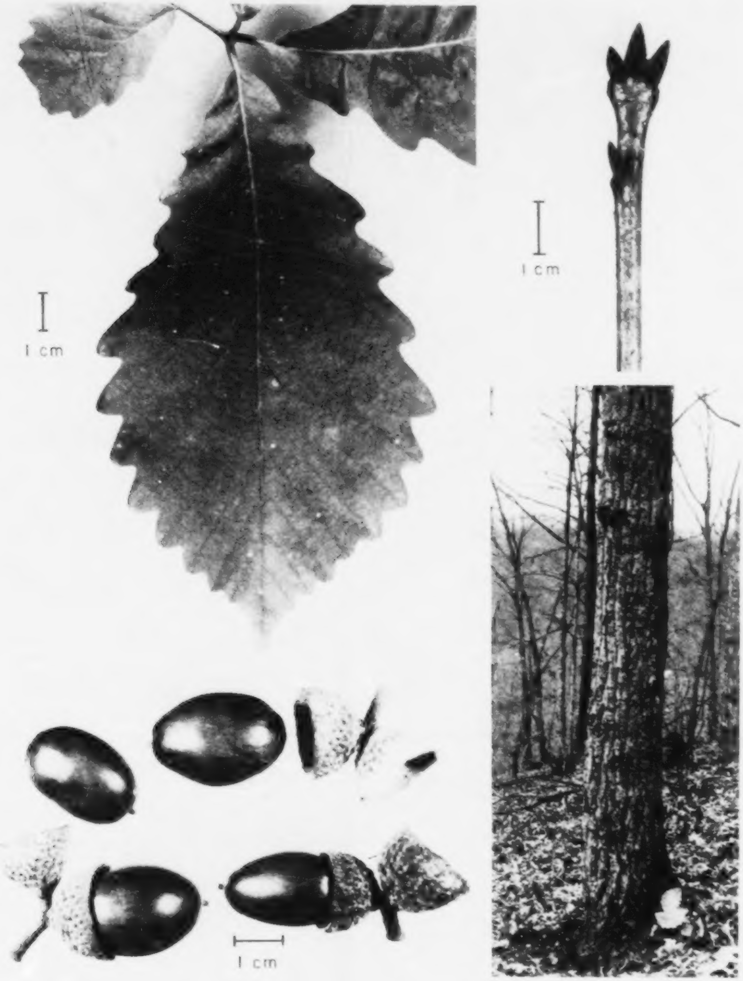
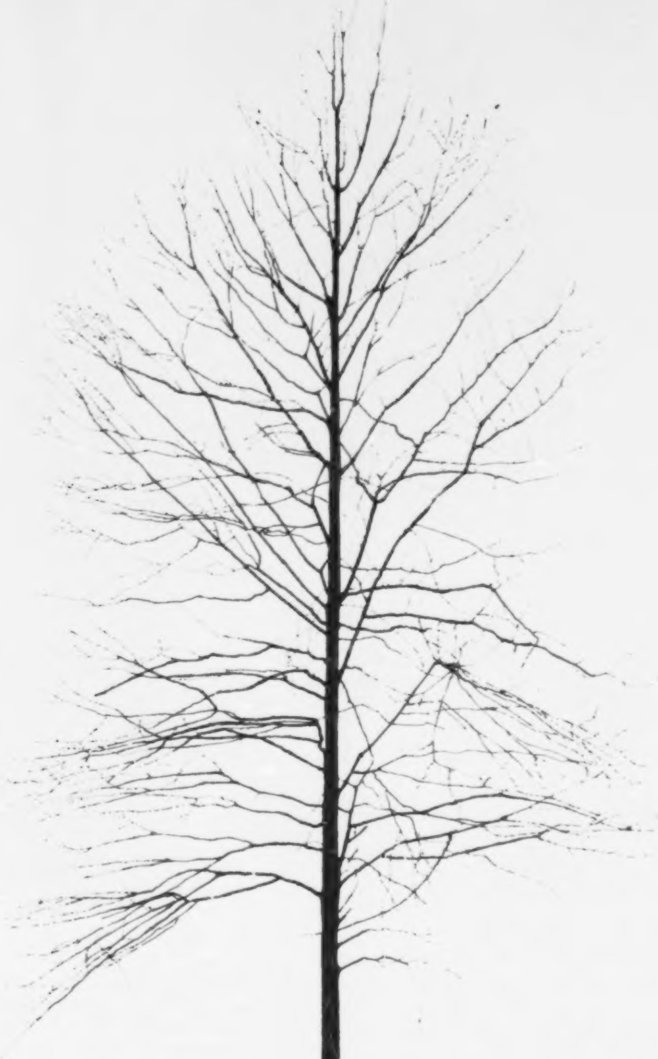


Figure 3-45.—Oak, chestnut (*Quercus prinus* L.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK dark reddish brown to nearly black, deeply furrowed with narrow ridges. BRANCHES stout, spreading to ascending. TWIGS stout, angulate, smooth, purplish-green when new, turning orange or reddish-brown. BUDS ovate-conical somewhat angulate, 8 to 12 mm long, silky hairy. LEAVES alternate, deciduous, simple; elliptic to obovate, 10 to 30 cm long, 3 to 8 cm wide, somewhat leathery, margin crenate with a vein ending in each rounded tooth, smooth green above, stellate-pubescent below. FLOWERS unisexual; staminate in catkins 5 to 10 cm long; pistillate in short spikes on stout peduncles. FRUIT an acorn 25 to 35 mm long, 15 to 25 mm in diameter; cup vase-shaped, thin, rough with thickened scales, covering ⅓ to ½ of the nut.

LAUREL OAK



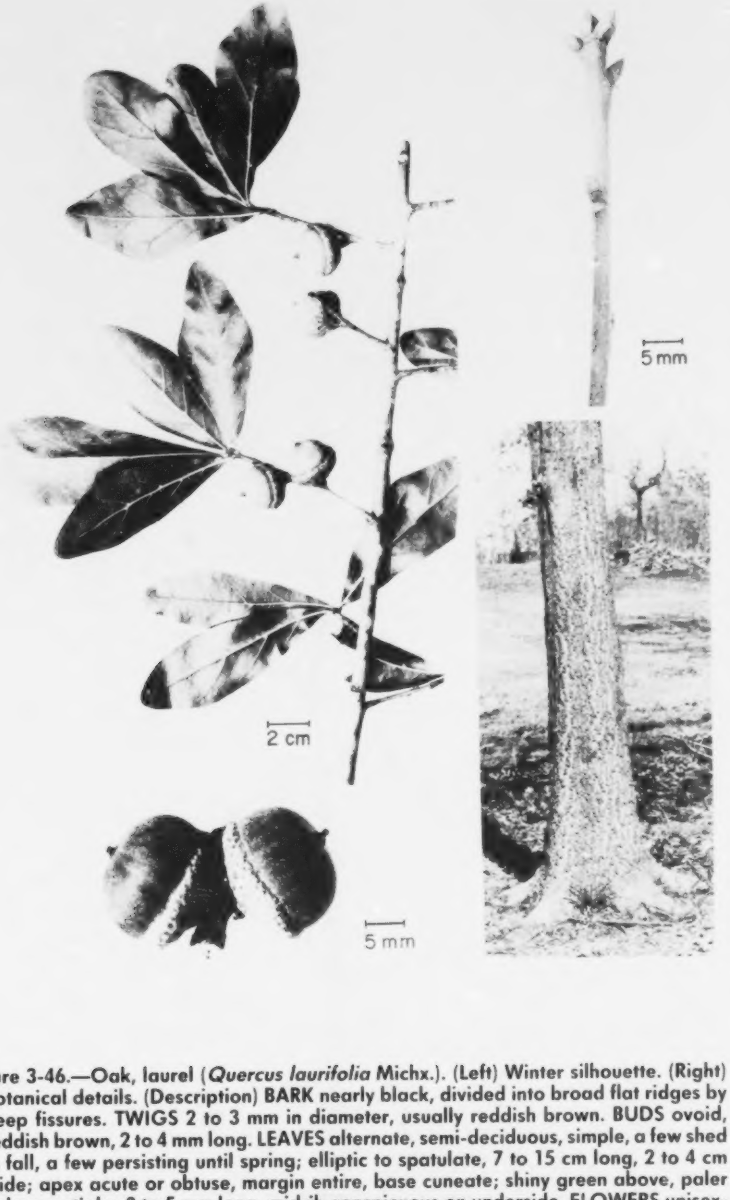
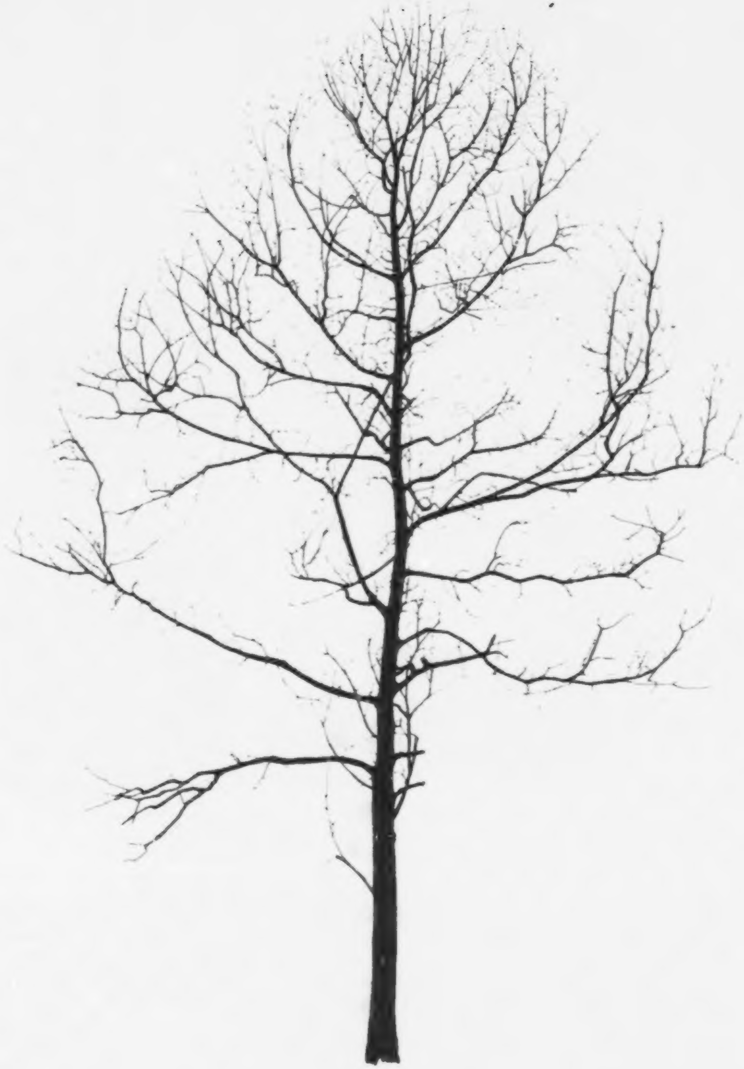


Figure 3-46.—Oak, laurel (*Quercus laurifolia* Michx.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK nearly black, divided into broad flat ridges by deep fissures. TWIGS 2 to 3 mm in diameter, usually reddish brown. BUDS ovoid, reddish brown, 2 to 4 mm long. LEAVES alternate, semi-deciduous, simple, a few shed in fall, a few persisting until spring; elliptic to spatulate, 7 to 15 cm long, 2 to 4 cm wide; apex acute or obtuse, margin entire, base cuneate; shiny green above, paler below; petioles 3 to 5 mm long, midrib conspicuous on underside. FLOWERS unisexual; staminate in catkins as leaves unfold; pistillate on twigs at leaf scars. FRUIT an acorn, sessile to subsessile, cup 15 to 20 mm wide, enclosing about ¼ of nut; nut hemispheric, rounded at apex and flattened at bottom, 15 mm long.

NORTHERN RED OAK



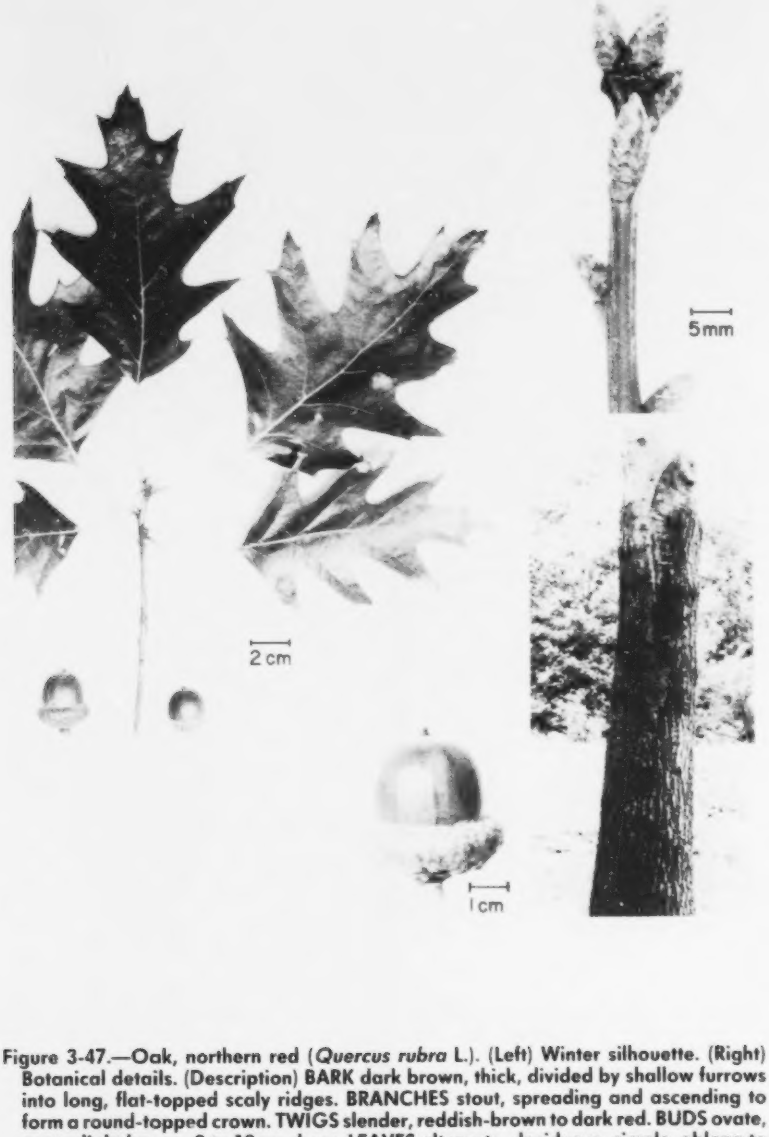
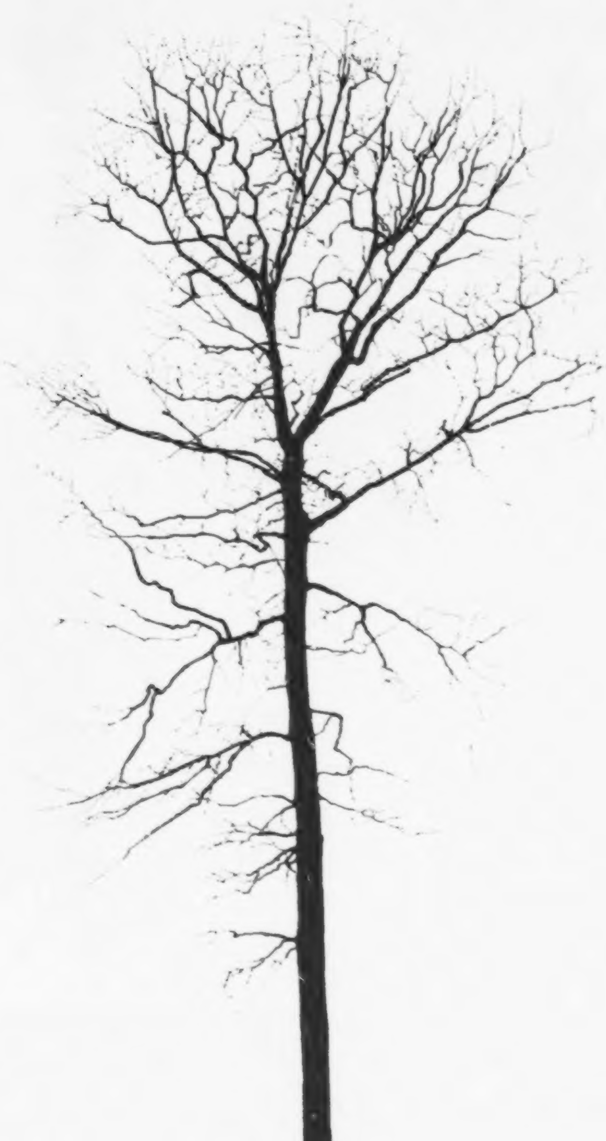


Figure 3-47.—Oak, northern red (*Quercus rubra* L.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK dark brown, thick, divided by shallow furrows into long, flat-topped scaly ridges. BRANCHES stout, spreading and ascending to form a round-topped crown. TWIGS slender, reddish-brown to dark red. BUDS ovate, acute, light brown, 8 to 10 mm long. LEAVES alternate, deciduous, simple, oblong to oval and obovate, 12 to 22 cm long, 10 to 15 cm wide; 7 to 11 short lobes, lobes 3-toothed, bristle-tipped; upper surface dull green. FLOWERS unisexual; staminate in slender catkins appearing with the developing leaves, pistillate inconspicuous on last year's wood. FRUIT an acorn, 15 to 30 mm long; cup saucer-shaped, enclosing about ¼ of the nut.

POST OAK



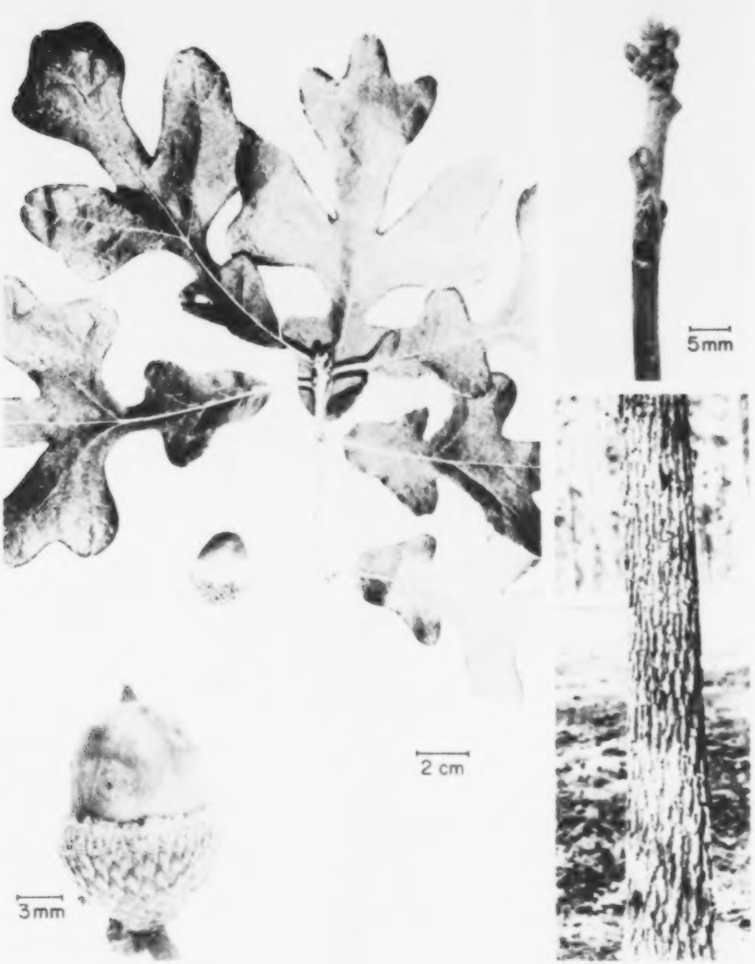
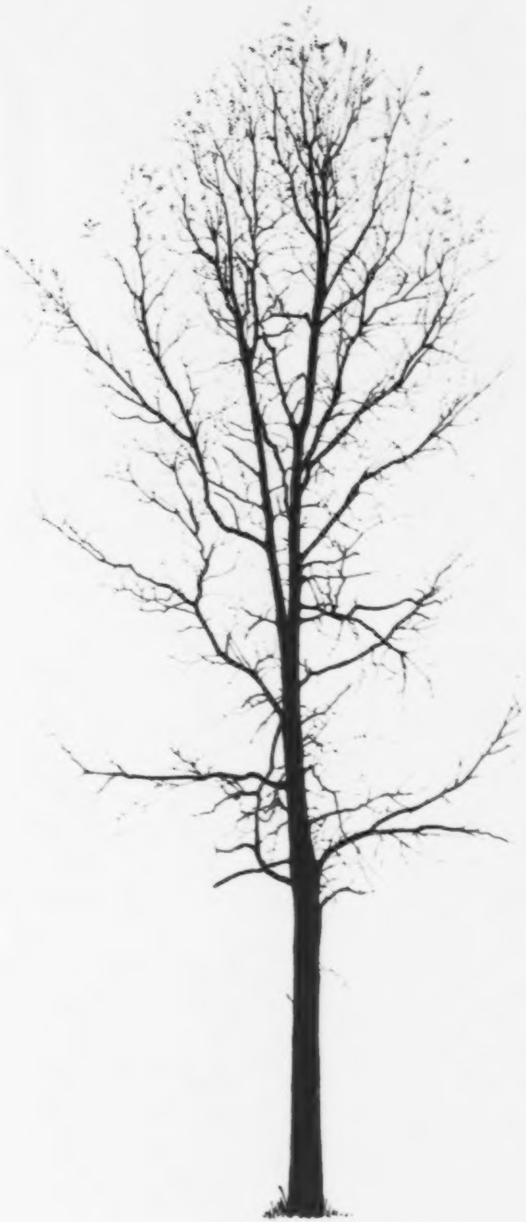


Figure 3-48.—Oak, post (*Quercus stellata* Wangenh.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK medium to dark gray, with deep furrows, scaly ridges. BRANCHES stout, irregular, drooping to horizontal and ascending. TWIGS 3 to 5 mm in diameter, gray to brownish. BUDS broadly ovate, blunt to acute, 5 mm long, clustered at apex of twig. LEAVES alternate, deciduous, simple; obovate, to 18 cm long, 5 to 10 cm wide; divided into 5 to 7 sinuate rounded lobes, the two lower lobes smaller than the upper pair, upper lobes and the terminal lobe resembling a cross, dark, shiny green above, grayish to brownish below, leathery. FLOWERS unisexual; staminate in catkins appearing with the unfolding leaves: pistillate on last year's wood. FRUIT an acorn 13 to 25 mm long, 6 to 25 mm wide; cup hemispherical, enclosing about ½ of the nut, cup scales rusty-pubescent; nut ovate to ovate-oblong, about 15 mm long.

SCARLET OAK



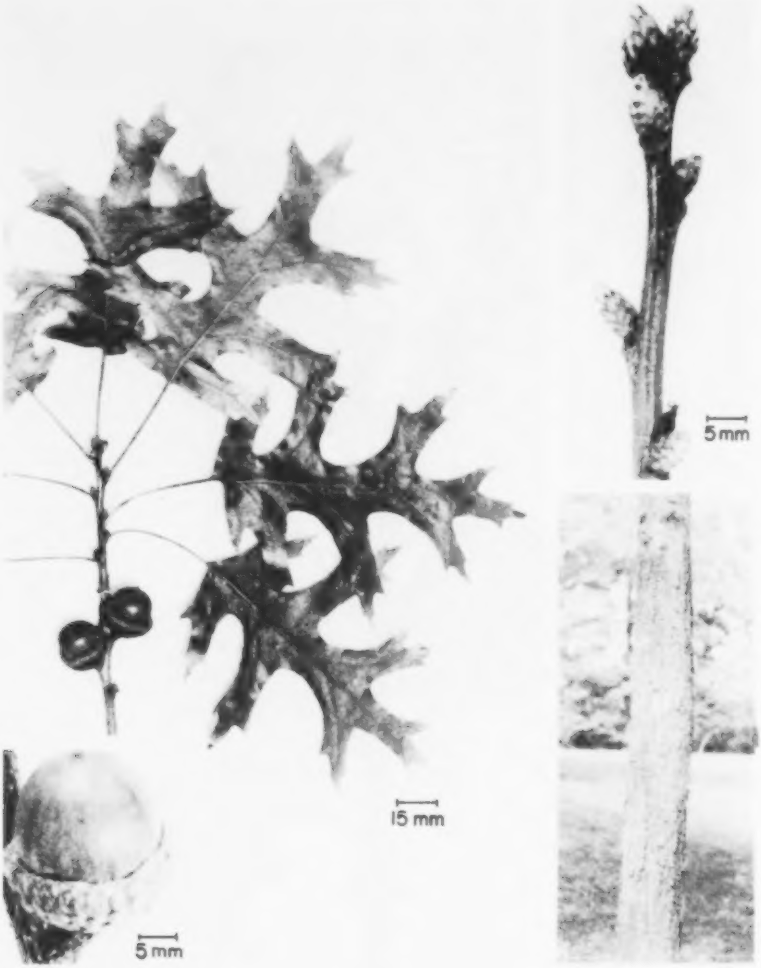
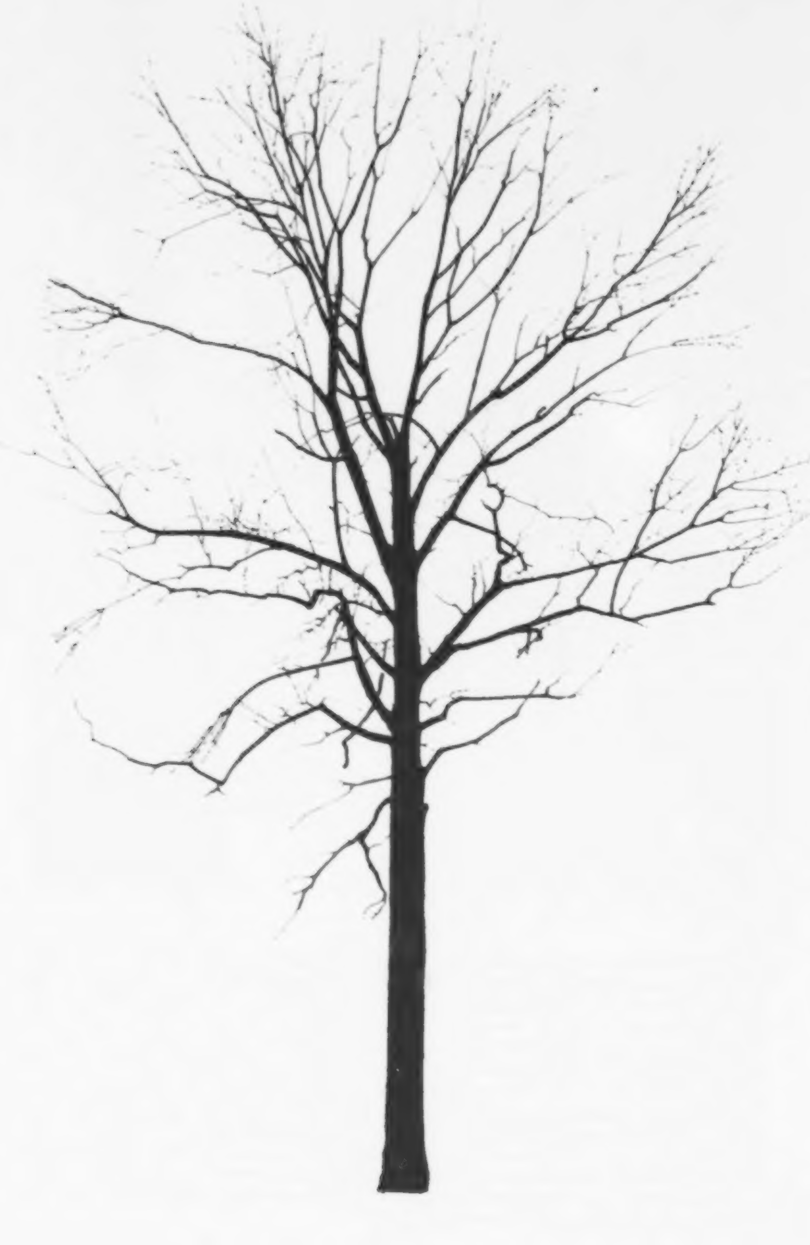


Figure 3-49—Oak, scarlet (*Quercus coccinea* Muenchh.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK dark grayish-black, divided into irregular fissures and scaly ridges. BRANCHES stout, spreading to ascending. TWIGS 3 to 4 mm in diameter, reddish, turning a dull red. BUDS ovoid, acute, 5 to 7 mm long, covered with rounded, lightly pubescent scales. LEAVES alternate, deciduous, simple; glabrous, except in axils of main veins on underside, oval to slightly obovate, 8 to 17 cm long, 5 to 13 cm wide, with 5 to 9 deep lobes often terminated by secondary lobes with bristle tips, sinuses usually deep, round, and wider than lobes; both surfaces pale green, upper surface shiny, bright scarlet in autumn, petioles about 4 cm long. FLOWERS unisexual; staminate in catkins with developing leaves; pistillate on pubescent peduncles. FRUIT an acorn; cup 15 to 30 mm wide, covered with brown scales enclosing about ⅓ to ½ of the nut; nut ovoid, 10 to 20 mm long, occasionally with ring grooves near apical point at maturity.

SHUMARD OAK



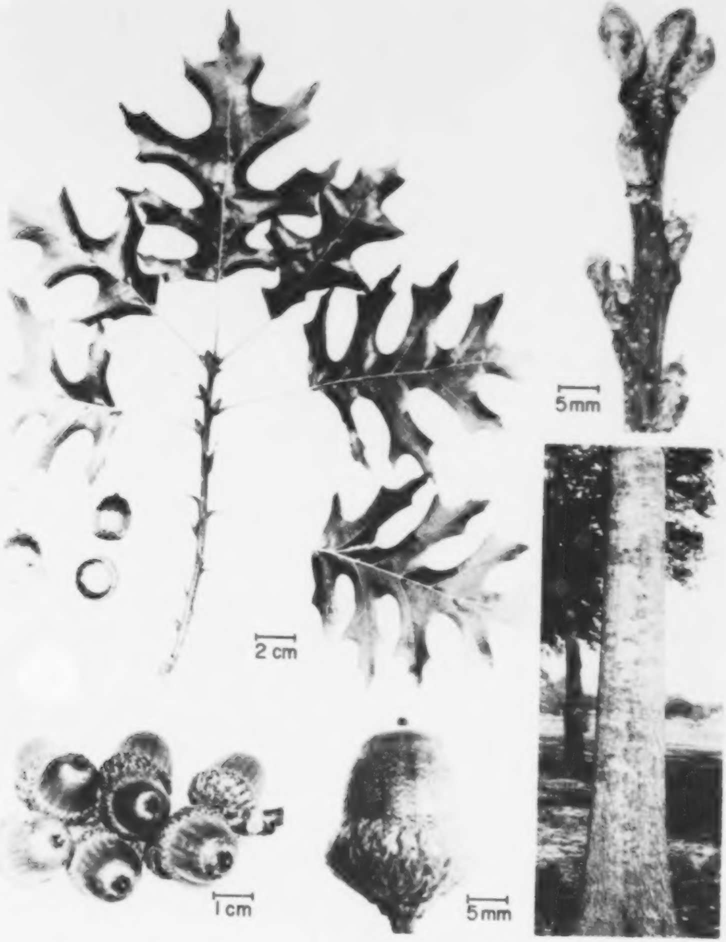
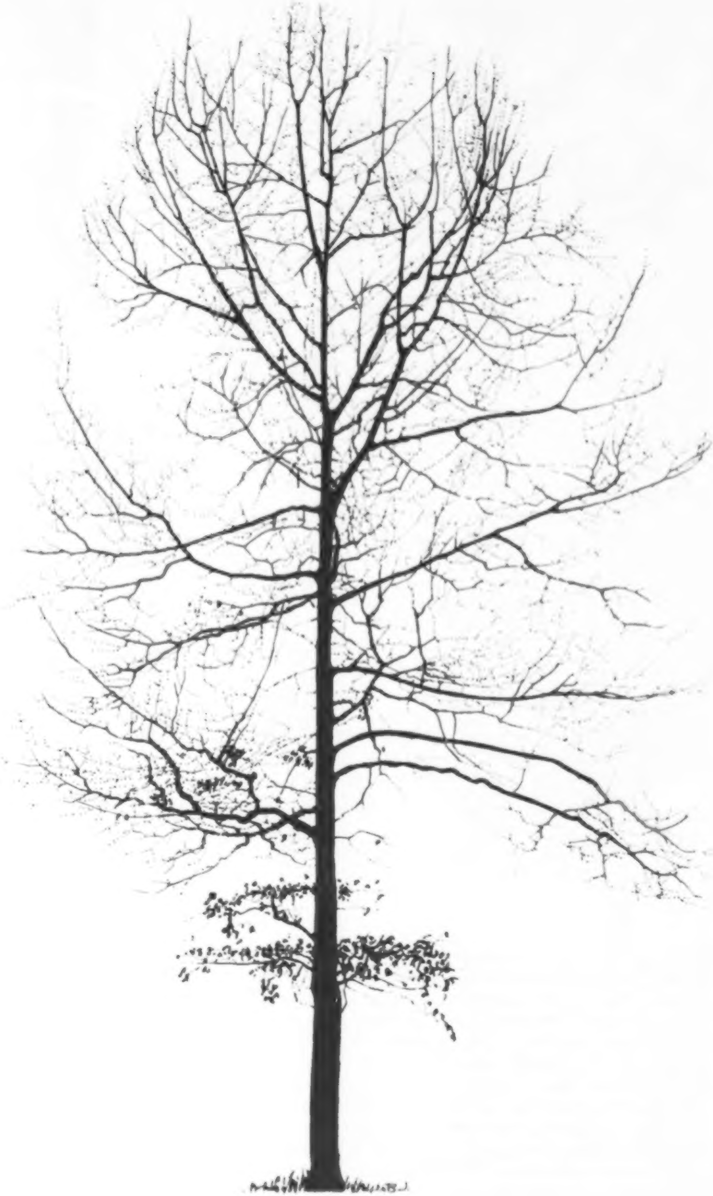


Figure 3-50.—Oak, Shumard (*Quercus shumardii* Buckl.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK dark gray to blackish, relatively smooth at first, then breaking into scaly ridges. BRANCHES spreading to ascending. TWIGS about 5 mm in diameter, olive green then turning dark reddish. BUDS clustered at apex, 5 to 7 mm long, sharp pointed, strongly angled. LEAVES alternate, deciduous, simple; oval to slightly obovate, 10 to 20 cm long, 6 to 15 cm wide; with 7 to 10 bristle-tipped lobes, lobes on upper crown leaves narrower to slightly wider than sinuses, lobes on lower crown leaves wider than sinuses; dark green above, paler below, glabrous except for vein axils on lower surface; petiole about 5 cm long. FLOWERS unisexual; staminate in yellow catkins appearing with the unfolding leaves; pistillate on pubescent peduncles. FRUIT an acorn; cup 20 to 31 mm across, enclosing about ¼ of the nut; nut about 25 mm long, 15 mm in diameter.

SOUTHERN RED OAK



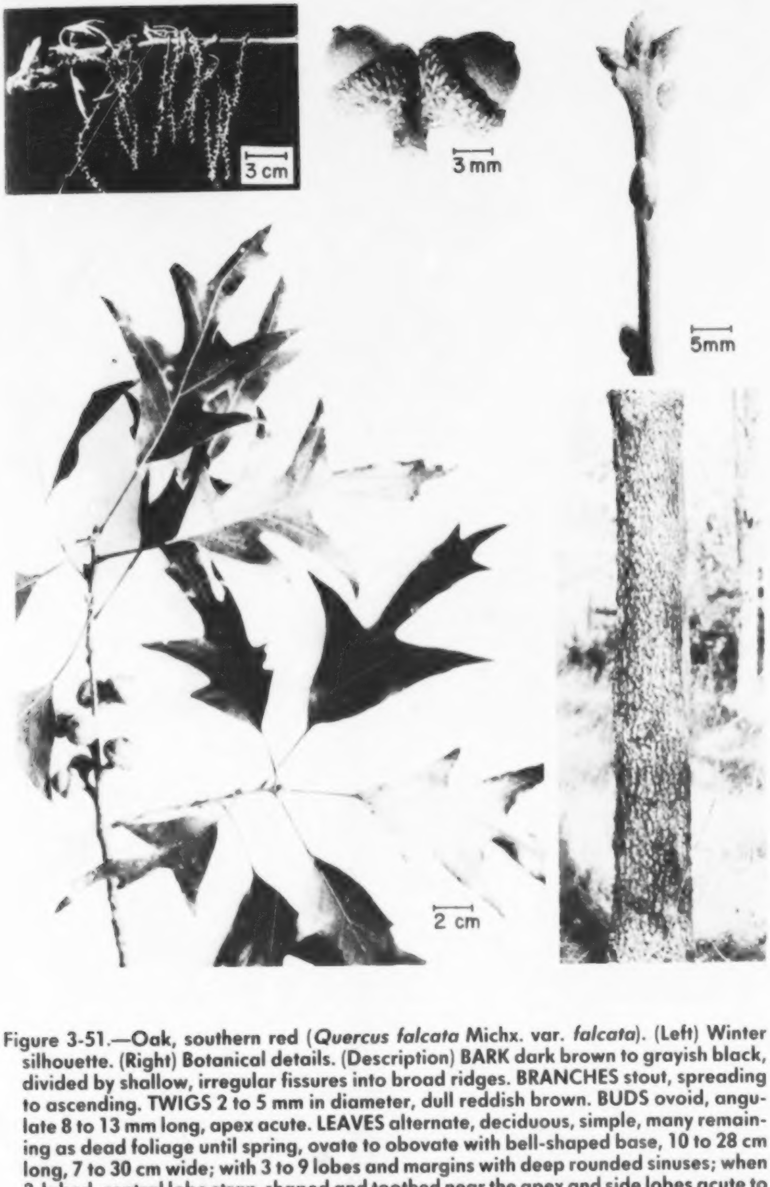
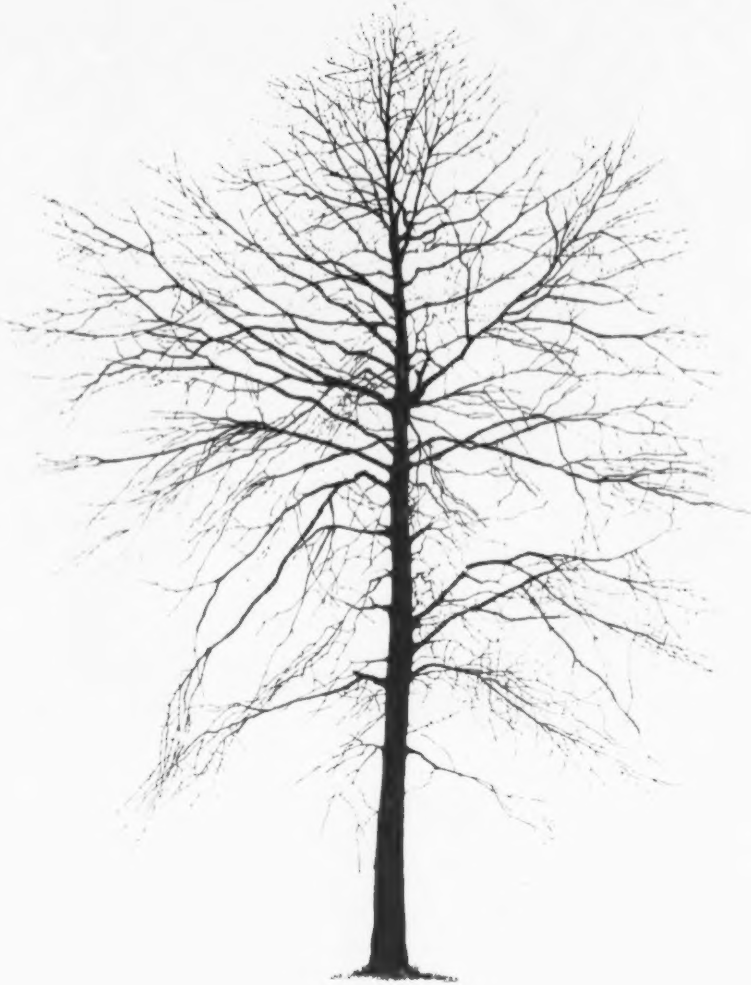


Figure 3-51.—Oak, southern red (*Quercus falcata* Michx. var. *falcata*). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK dark brown to grayish black, divided by shallow, irregular fissures into broad ridges. BRANCHES stout, spreading to ascending. TWIGS 2 to 5 mm in diameter, dull reddish brown. BUDS ovoid, angulate 8 to 13 mm long, apex acute. LEAVES alternate, deciduous, simple, many remaining as dead foliage until spring, ovate to obovate with bell-shaped base, 10 to 28 cm long, 7 to 30 cm wide; with 3 to 9 lobes and margins with deep rounded sinuses; when 3-lobed, central lobe strap-shaped and toothed near the apex and side lobes acute to acuminate, somewhat falcate; permanently pubescent below, white at first, turning rust. FLOWERS unisexual, staminate in tomentose catkins as leaves unfold; pistillate in leaf axils on twigs. FRUIT an acorn, small, spherical to hemispherical; cup 12 to 15 mm wide, shallow saucer-shaped, enclosing about ¼ to ½ of the nut; nut 8 to 12 mm long.

WATER OAK



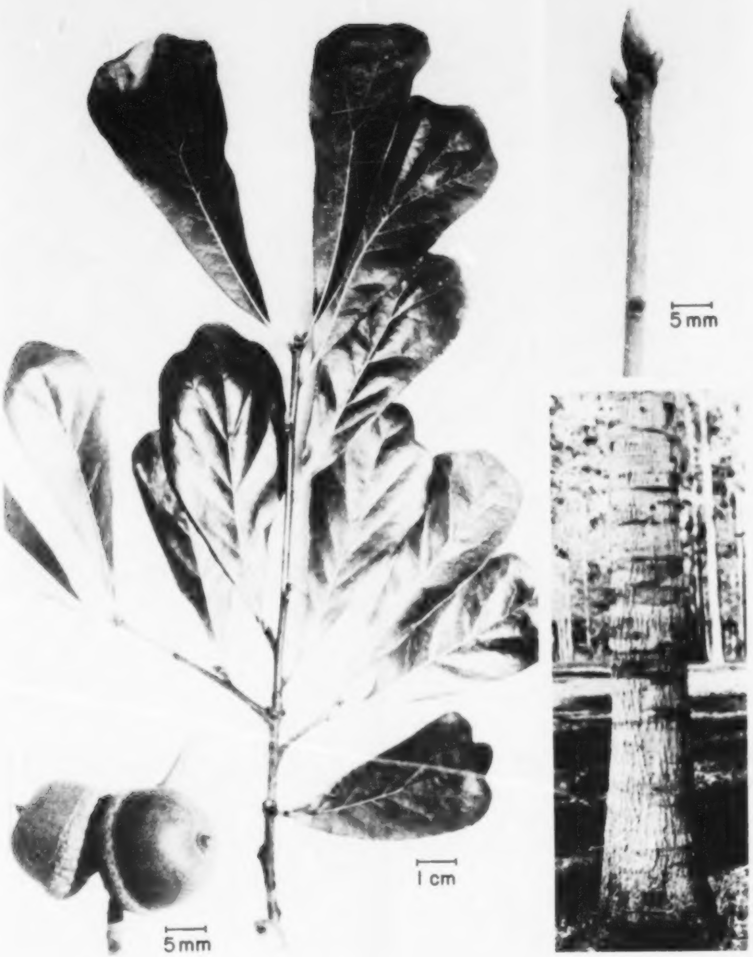
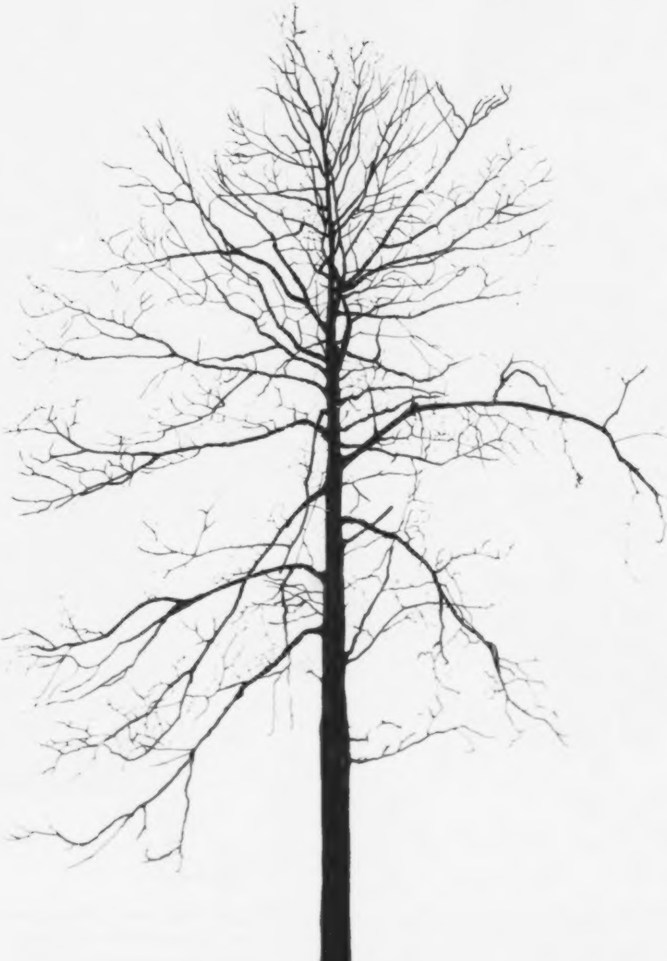


Figure 3-52.—Oak, water (*Quercus nigra* L.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK smooth, grayish black, becoming scaly with age. BRANCHES spreading to ascending, forming a round-topped crown in the open. TWIGS 3 to 5 mm in diameter, gray. BUDS ovoid, acute, reddish brown, 3 to 7 mm long. LEAVES alternate, deciduous, simple; variable in shape and size, obovate to spatulate, 5 to 10 cm long, 2 to 5 cm wide; margin entire, wavy to distinctly lobed in juvenile specimens; sessile or with petiole to 1 cm long. FLOWERS unisexual; staminate catkins 5 to 8 cm long, pistillate catkins short-peduncled. FRUIT an acorn about 15 mm wide, 10 mm high; cup thin, enclosing about 1/5 to 1/3 of the nut.

WHITE OAK



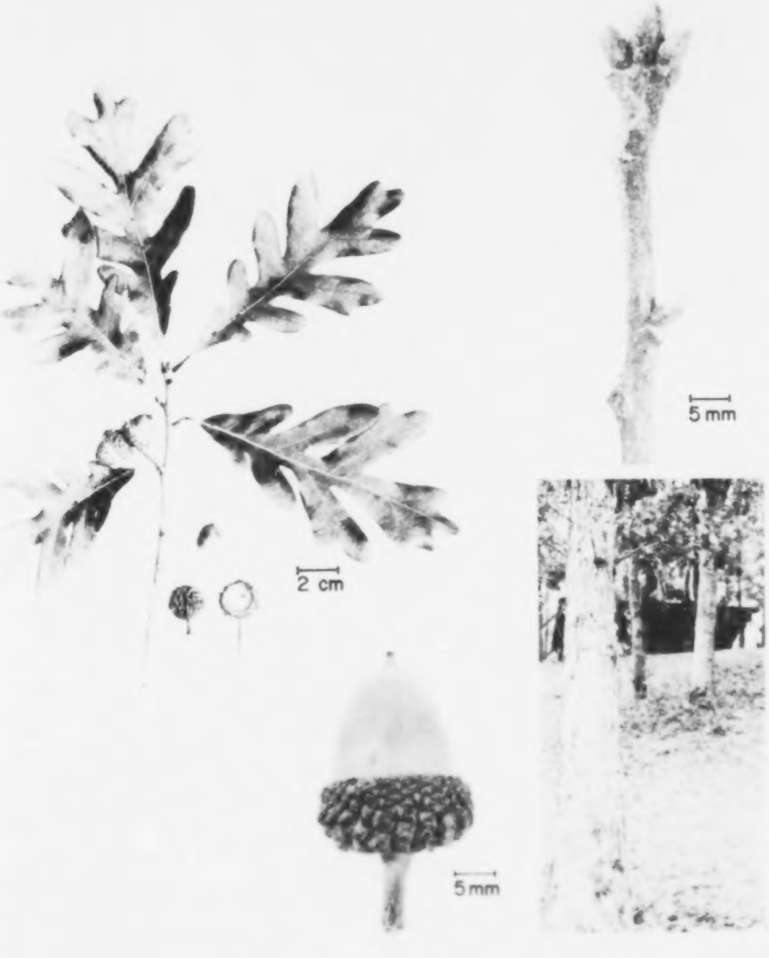
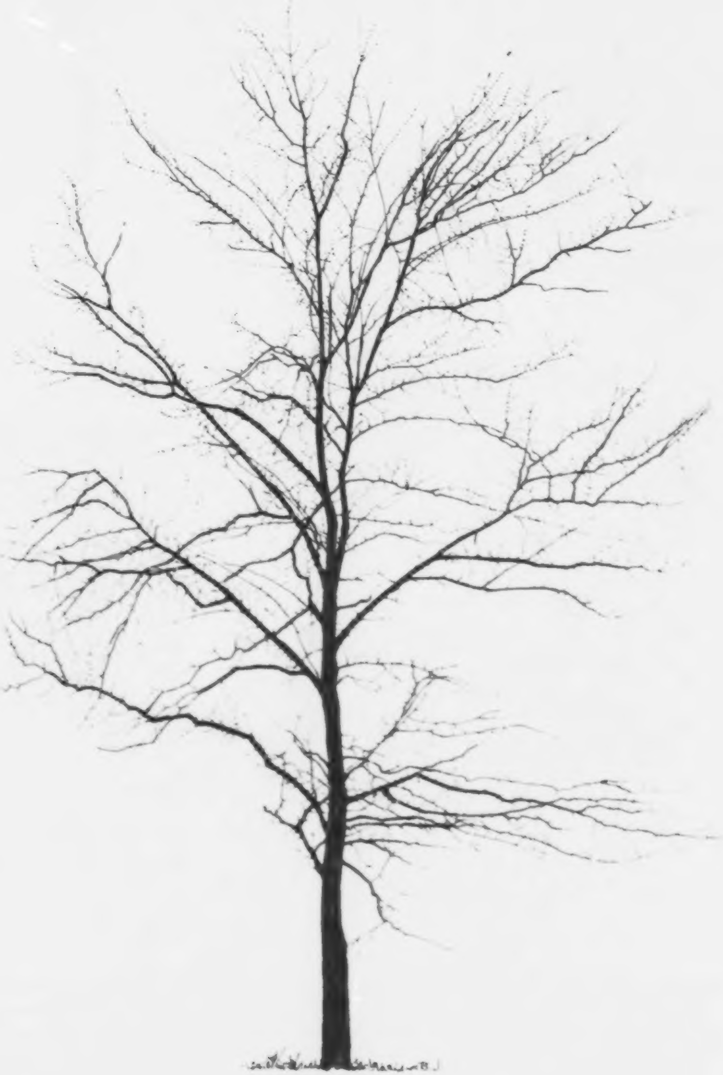


Figure 3-53.—Oak, white (*Quercus alba* L.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK light gray, separated by shallow furrows into flat ridges with loose appressed scales. BRANCHES stout, drooping, spreading to ascending. Twigs 2 to 3 mm in diameter, reddish. BUDS globose to ovoid, angulate, apex acute to obtuse, 3 to 5 mm. LEAVES alternate, deciduous, simple, oblong to obovate, 7 to 20 cm long, 4 to 10 cm wide, with 7 to 11 uneven, rounded lobes and deep sinuses. FLOWERS unisexual in catkins, preceding leaf expansion. FRUIT an acorn 15 to 35 mm long, 20 to 25 mm in diameter, cup 1-½ to 3 cm wide, usually cup-shaped, conspicuous with thickened scales, enclosing ¼ to ⅓ of the nut.

SUGARBERRY



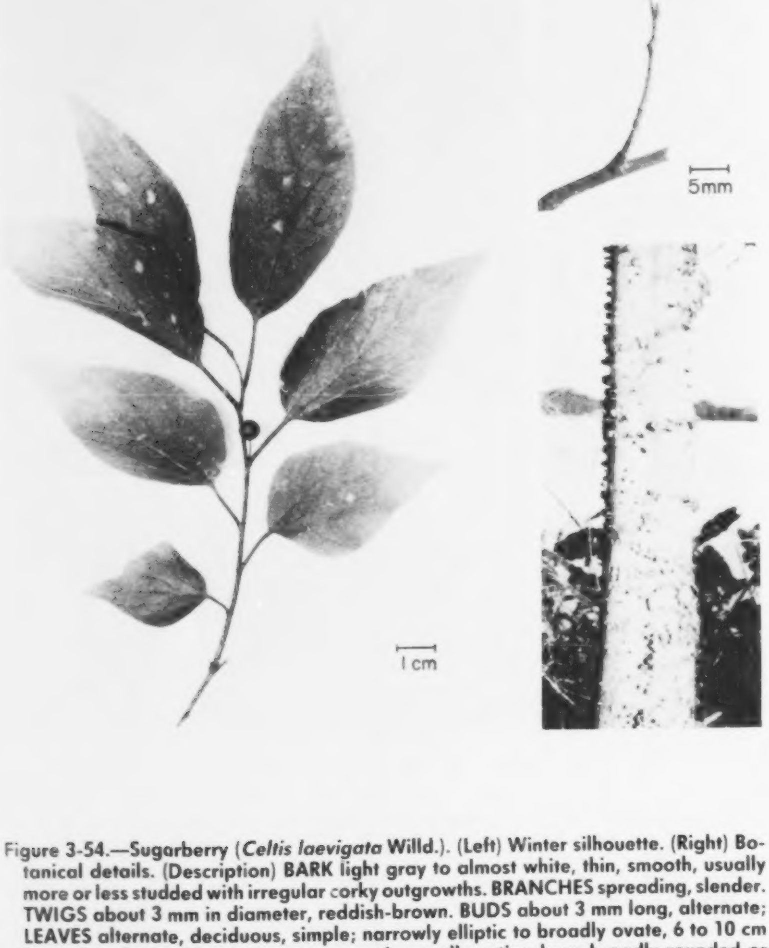
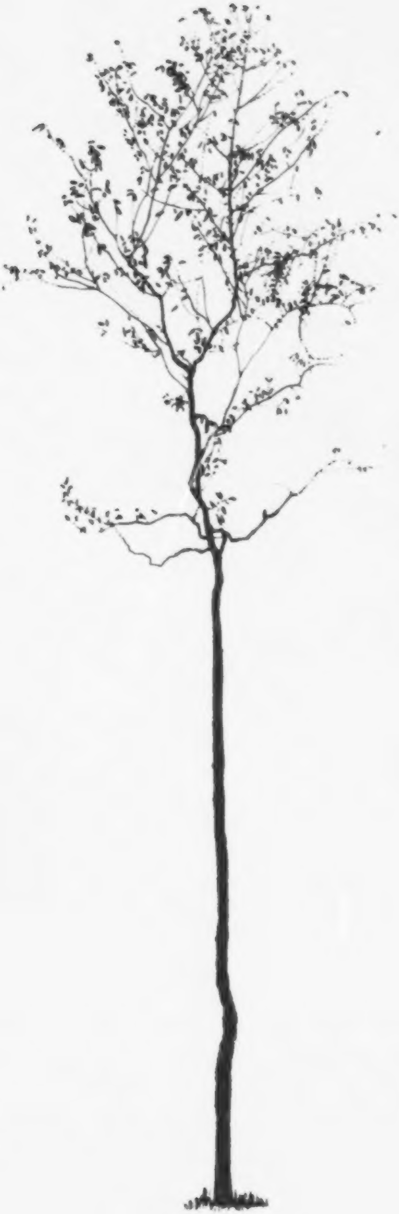


Figure 3-54.—Sugarberry (*Celtis laevigata* Willd.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK light gray to almost white, thin, smooth, usually more or less studded with irregular corky outgrowths. BRANCHES spreading, slender. TWIGS about 3 mm in diameter, reddish-brown. BUDS about 3 mm long, alternate; LEAVES alternate, deciduous, simple; narrowly elliptic to broadly ovate, 6 to 10 cm long, 2 to 4 cm wide; apex acute, margin usually entire, base broadly rounded or oblique. FLOWERS unisexual or perfect, tiny, inconspicuous, many staminate and few pistiilate appearing on the new growth as the leaves unfold. FRUIT a drupe with a bony reticulated nutlet, about 5 mm in diameter, orange-red on a pedicel often shorter than the petiole of the subtending leaf.

SWEETBAY



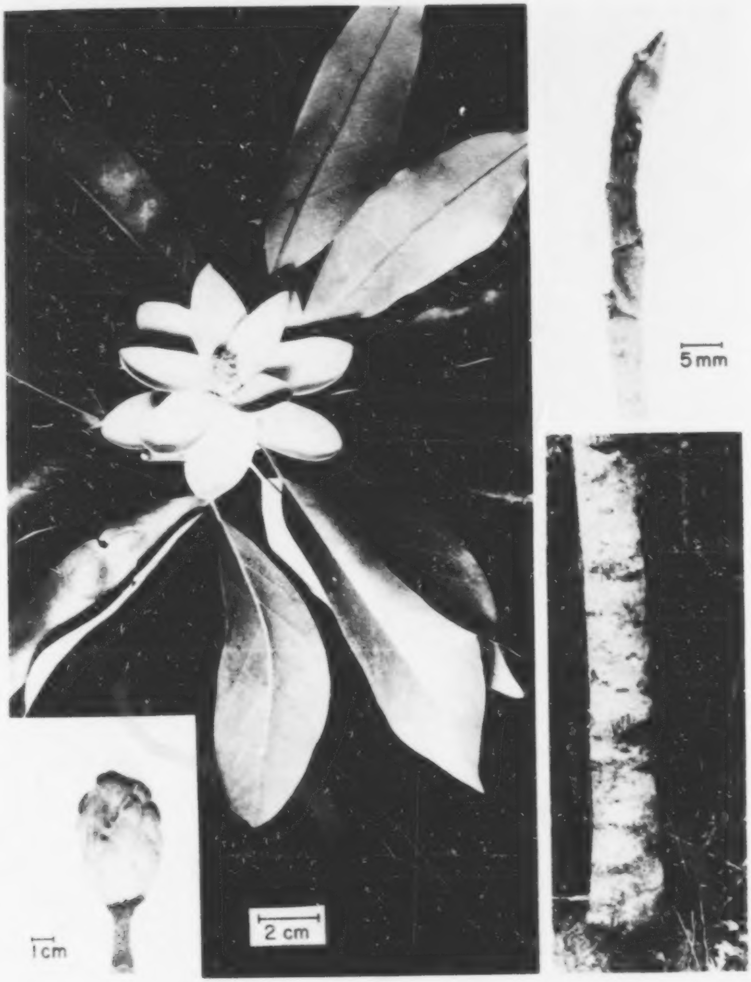
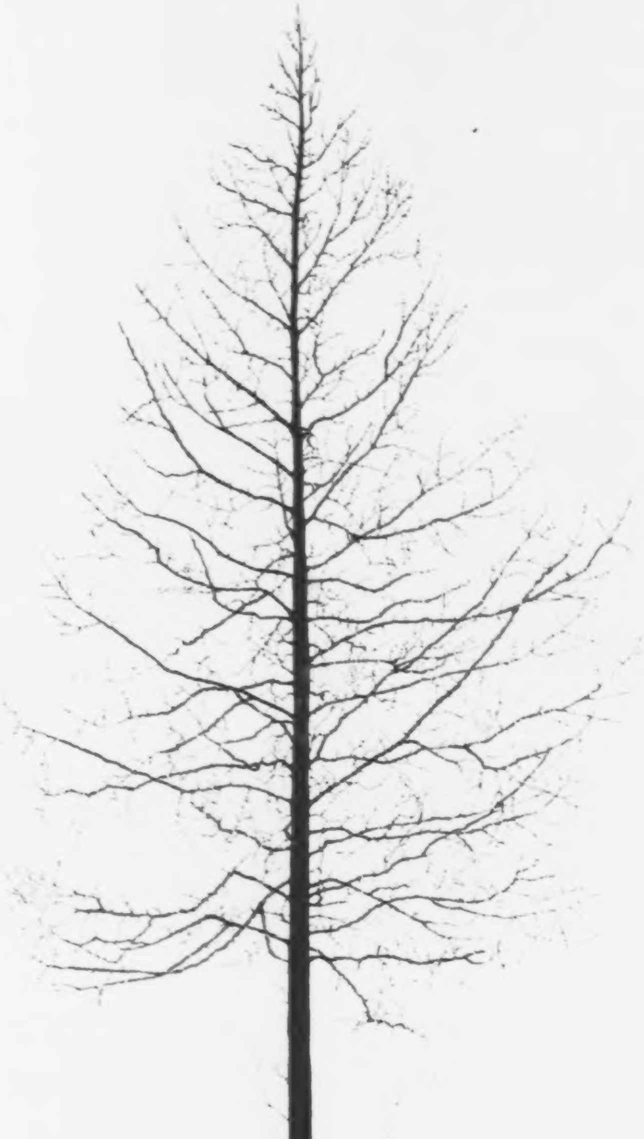


Figure 3-55.—Sweetbay (*Magnolia virginiana* L.). (Left) Winter silhouette in southern range. (Right) Botanical details. (Description) BARK dark gray, usually smooth, thin, in shady areas often encrusted with mosses, liverworts, and lichens. BRANCHES stout, spreading to ascending. TWIGS about 5 to 7 mm in diameter, encircled by stipule scars, green. BUDS (terminal), silvery gray, pubescent 15 mm long; smaller lateral buds often subtended by persistent petiole base. LEAVES alternate, evergreen in South, deciduous in northern part of range, simple; elliptic to oblong, 10 to 15 cm long, 4 to 6 cm wide; margin entire, dark green above, silvery pubescent below. FLOWERS perfect, white, sweet-scented, 5 to 8 cm in diameter, appearing May to September. FRUIT an aggregate of follicles which open and shed red seeds, irregular in shape, ovoid to ellipsoid, smooth, about 5 cm long.

SWEETGUM



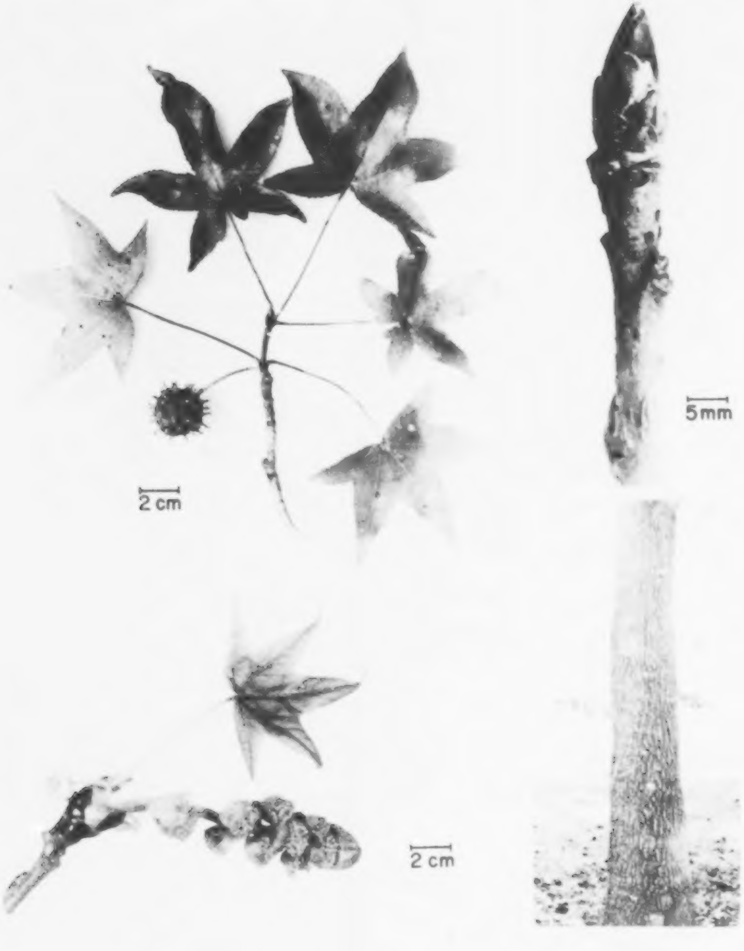
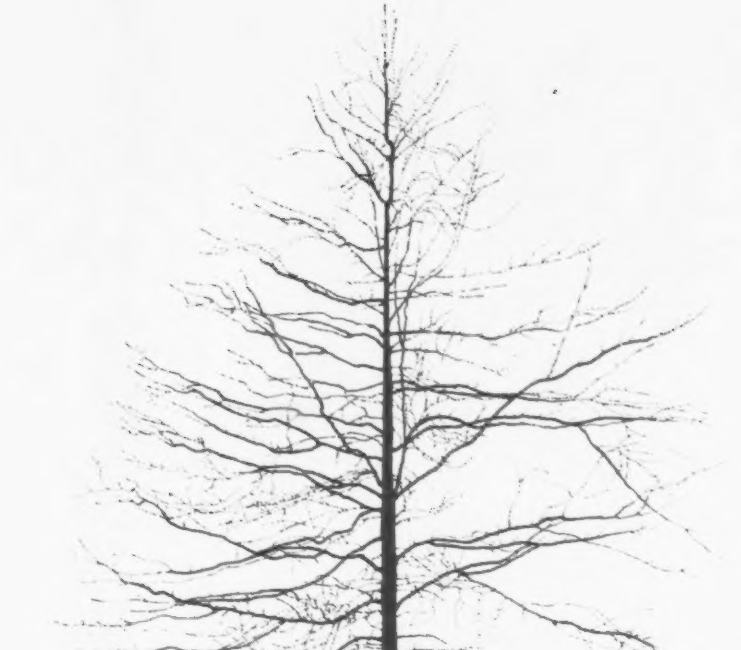


Figure 3-56.—Sweetgum (*Liquidambar styraciflua* L.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK dark gray, divided by deep furrows into narrow, rounded ridges. BRANCHES stout, often with corky wings or outgrowths. TWIGS about 4 to 6 cm in diameter, gray-brown. BUDS (terminal) broadly egg-shaped, about 10 to 15 mm long, scales overlapping, slightly sticky. LEAVES alternate, deciduous, simple; palmately 5- to 7-lobed; 8 to 20 cm wide, 6 to 15 cm long, often longer than broad; margin finely serrate; petioles 4 to 13 cm long. FLOWERS unisexual (plants monoecious), appearing as the leaves unfold, staminate clustered in terminal racemes, pistillate in small drooping spherical heads. FRUIT in stalked spherical heads covered with small spine-like projections; seed cavity at base of each spine.

BLACK TUPELO



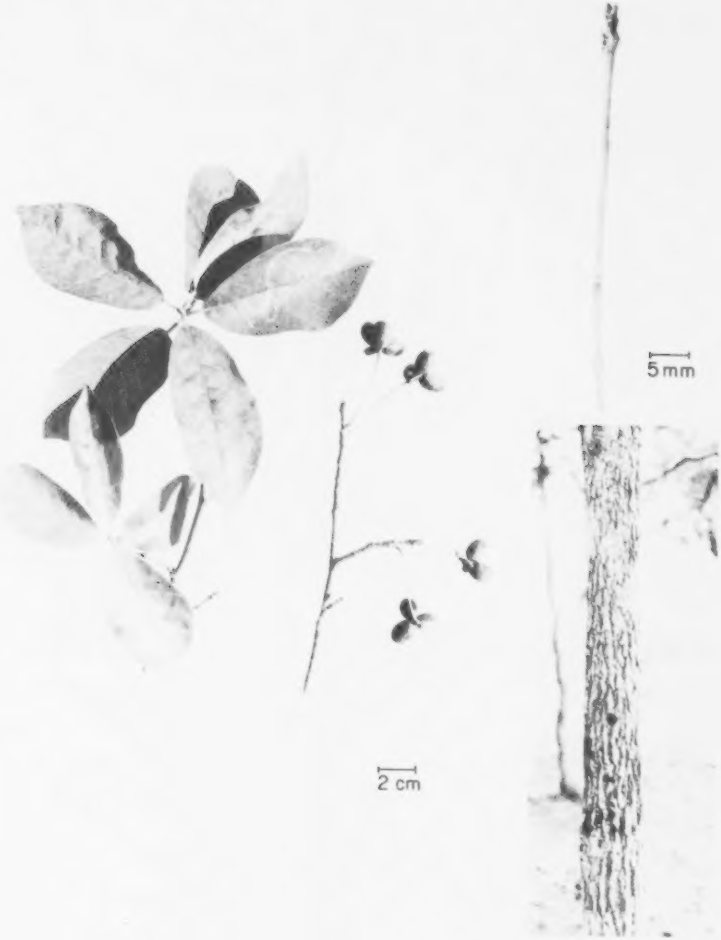
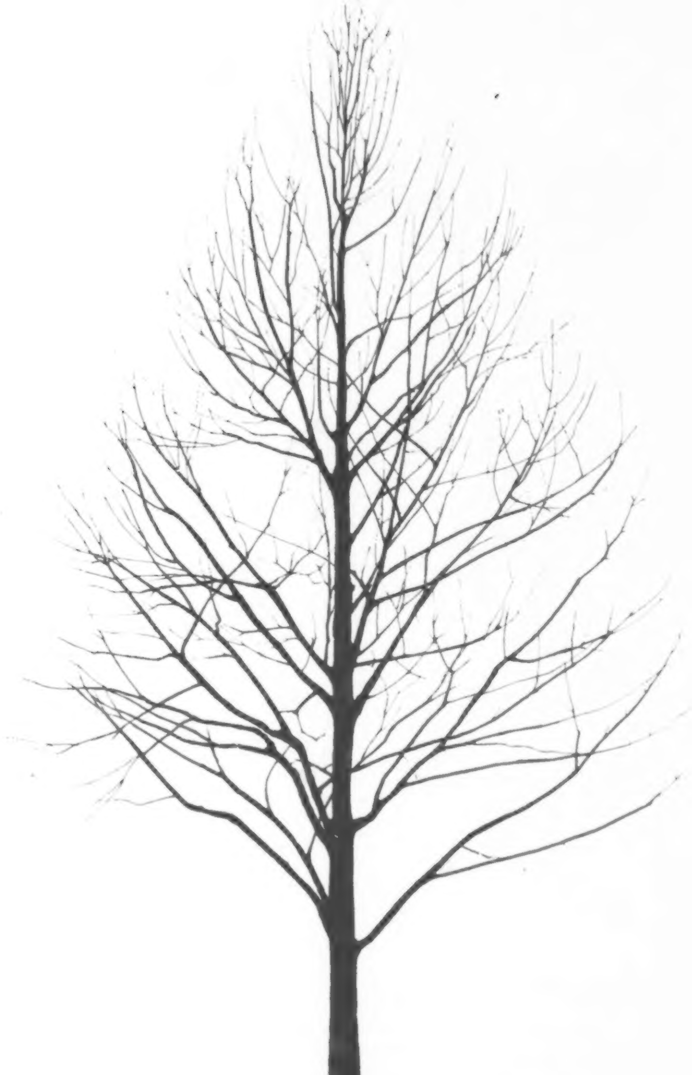


Figure 3-57.—Tupelo, black (*Nyssa sylvatica* Marsh.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK black, marked with furrows and cross-cracks that divide the ridges into squarish plates. BRANCHES slender, spreading to horizontal, often drooping in open-grown specimens. TWIGS 2 to 3 mm in diameter, gray to reddish. BUDS obtuse, of overlapping yellow-brown scales, terminal buds 6 mm long. LEAVES alternate, early deciduous, simple; marked with irregular black spots and purple coloration from midsummer on; elliptic to broadly oval to obovate, 5 to 15 cm long, 3 to 8 cm wide; apex acute to broadly rounded, margin entire, base wedge-shaped. FLOWERS unisexual, less than 4 mm in diameter, appearing in April before leaf expansion. FRUIT a black drupe 8 to 10 mm long, 1 to 3 on pedicels 3 to 5 cm long, stone faintly ribbed.

YELLOW-POPLAR



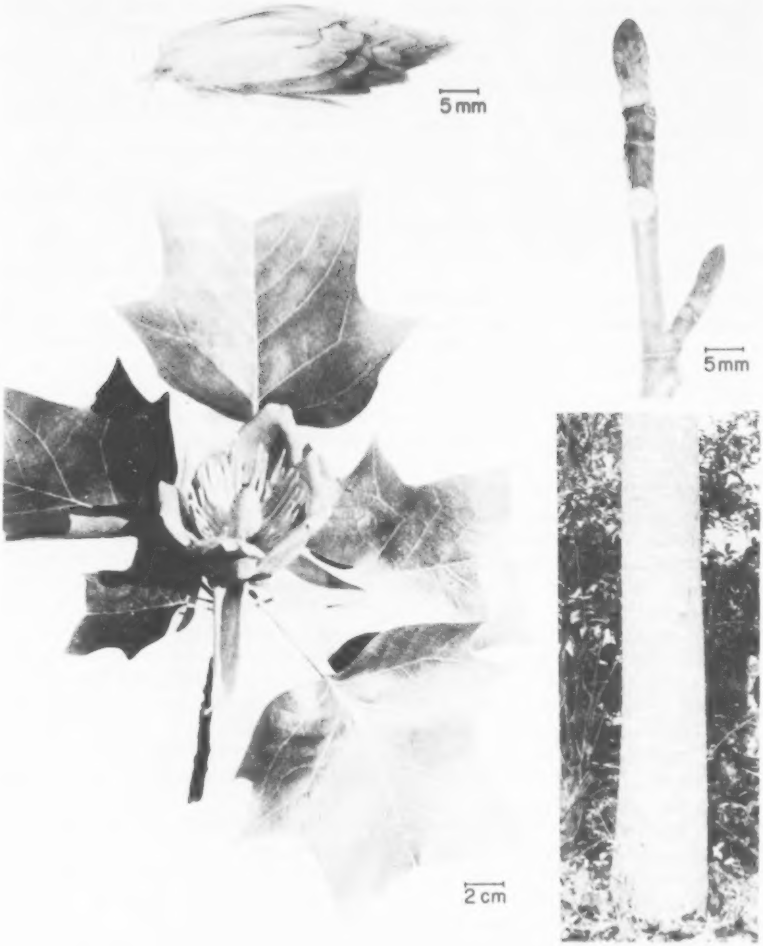


Figure 3-58.—Yellow-poplar (*Liriodendron tulipifera* L.). (Left) Winter silhouette. (Right) Botanical details. (Description) BARK thin and dark green on young trees, becoming ash-gray and conspicuously furrowed and ridged with age. BRANCHES spreading to ascending, often drooping on large open-grown trees. TWIGS smooth, about 5 mm in diameter, encircled by stipule scars, red-brown. BUDS (terminal) grayish green, turning red in winter, flat about 10 to 16 mm long, scales valvate. LEAVES alternate, deciduous, simple; dark green above, turning yellow in fall; 6 to 20 cm long and as wide as long; petioles 5 to 20 cm long, often longer than the blades on low branches. FLOWERS perfect, tulip-shaped, about 4 to 6 cm long, greenish-yellow with orange to reddish markings at base of petals, color intensifies with age. FRUIT an aggregate cone, 5 to 8 cm long, gradually shattering into one-seeded, winged samaras.

3-3 LITERATURE CITED

Allen, R. H., Jr. and D.A. Marquis. 1970. Effect of thinning on height and diameter growth of oak & yellow-poplar saplings. U.S. Dep. Agric. For. Serv., Res. Pap. NE-173. 11p.

Arend, J.L. and O. Julander. 1948. Oak sites in the Arkansas Ozarks. Agric. Exp. Stn. Bull. 484, 42p. Univ. of Ark. Coll. of Agric., Fayetteville, Ark.

Bailey, L.H. 1949. Manual of cultivated plants. Rev., 1116 p. New York, N.Y.: Macmillan Co.

Baudendistel, M.E. and B.H. Paul. 1944. Southern hard elms as substitutes for rock elm. South. Lumberman 169(2129):211-215.

Beck, D.E. 1962. Yellow-poplar site index curves. U.S. Dep. Agric. For. Serv., Res. Note 180. 2p. Southeast. For. Exp. Stn., Asheville, N.C.

Beck, D.E. 1975. Growth and yield of yellow-poplar, potential for management. *In* Impact of inflation on the management and utilization of hardwoods yellow-poplar sem., proc. of the third annu. hardwood symp. of the Hardwood Res. Counc., pp. 51-59.

Beck, D.E. and L. Della-Bianca. 1970. Yield of unthinned yellow-poplar. U.S. Dep. Agric. For. Serv., Res. Pap. SE-58. 20p.

Beck, D.E. and L. Della-Bianca. 1972. Growth and yield of thinned yellow-poplar. U.S. Dep. Agric. For. Serv., Res. Pap. SE-101. 20p.

Bishop, G.N. and T.C. Nelson. 1955. A winter key to the hickories of Georgia. U.S. Dep. Agric. For. Serv., Res. Note No. 89, 2 p. Southeast. For. Exp. Stn., Asheville, N.C.

Blackmon, B.G. and W.M. Broadfoot. 1970. Fertilizer improves poplar growth. Miss. Farm Res. 33(11):7.

Boisen, A.T. and J.A. Newlin. 1910. The commercial hickories. U.S. Dep. Agric. For. Serv., Bull. 80. 64 p.

Boner, F.T. 1976. Storage and stratification recommendations for pecan and shagbark hickory. U.S. Dep. Agric. For. Serv., Tree Plant. Notes 27(4):3-5.

Broadfoot, W.M. 1976. Hardwood suitability for and properties of important Midsouth soils. U.S. Dep. Agric. For. Serv., Res. Pap. SO-127. 84 p.

Broadfoot, W.M. and R.M. Krinard. 1959. Guide for evaluating sweetgum sites. U.S. Dep. Agric. For. Serv., Occas. Pap. 176, 8 p.

Broadfoot, W.M. 1963. Guide for evaluating water oak sites. U.S. Dep. Agric. For. Serv., Res. Pap. SO-1. 8 p.

Broadfoot, W.M. 1969. Problems in relating soil to site index for southern hardwoods. For. Sci. 15(4):354-364.

Broadfoot, W.M. 1970. Tree-character relations in southern hardwood stands. U.S. Dep. Agric. For. Serv., Res. Note SO-98. 7 p.

Brown, C.A. 1945. Louisiana trees and shrubs. Bull. 1, 262 p. Baton Rouge, La.: La. For. Comm.

Brown, C.A., and H.E. Grelen. 1977. Identifying hardwoods growing on southern pine sites. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. SO-15. 69.p.

Brown, C.L., and R.G. McAlpine. 1964. Propagation of sweetgum from root cuttings. Ga. For. Res. Pap. 24, 5 p. Ga. For. Res. Counc., Macon, Ga.

Caldwell, D.H. 1953. Natural variation observed in shagbark hickory, *Carya ovata* (Mill.) K. Koch, in central New York. Rep. North. Nut Growers' Assoc. 44:29-39.

Carmean, W.H. 1971a. Site index curves for black, white, scarlet, and chestnut oaks in the Central States. U.S. Dep. Agric. For. Serv., Res. Pap. NC-62. 8p.

Carmean, W.H. 1971b. Soil-site relationships of the upland oaks. *In* Oak symp. proc., pp. 23-29. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Carvell, K.L. 1971. Silvicultural aspects of intermediate cuttings. *In* Oak symp. Proc., pp. 60-64. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Chen, P.Y.S. and R.C. Schlesinger. 1973. Elm—an American wood. U.S. Dep. Agric. For. Serv., Leafl. FS-233. 7 p.

Christopher, J.F., H.S. Sternitzke, R.C. Beltz, J.M. Earles, and M.S Hedlund. 1976. Hardwood distribution on pine sites in the South. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-59. 27 p.

Clark, F.B. 1970. Measures necessary for natural regeneration of oaks, yellow-poplar, sweetgum, and black walnut. *In* The silviculture of oaks and associated species. U.S. Dep. Agric. For. Serv., Res. Pap. NE-144. p. 1-16.

Clark, F.B. and R.F. Watt. 1971. Silvicultural methods for regenerating oaks. *In* Oak symp. proc., pp. 37-43. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Clark, F.B. and F.G. Liming. 1957. Low-grade hardwood stands in the Missouri Ozarks respond to stand improvement. J. of For. 55(5):354-358.

Clark, F.B. and F.G. Liming. 1953. Sprouting of blackjack oak in the Missouri Ozarks. U.S. Dep. Agric. For. Serv., Tech. Pap. No. 137. 23 p. Cent. States For. Exp. Stn., Columbus, Ohio.

Clark, A., III. 1973. Pecan—an American wood. U.S. Dep. Agric. For. Serv., Leafl. FS-249. 8 p.

Collingwood, G.H. and W.D. Brush. 1974. Knowing your trees. Rev., 374 p. Amer. For. Assoc., Washington, D.C.

Cooper, G.A. and R.F. Watt. 1973. Oak—an American wood. U.S. Dep. Agric. For. Serv., Leafl. FS-247. 9 p.

Core, E.L. 1971. Silvical characteristics of the five upland oaks. *In* Oak symp. proc., pp. 19-22. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Correll, D.C. and M.C. Johnston. 1970. Manual of the vascular plants of Texas. Contributions from the Tex. Res. Found., Vol. 6. 1881 p. Renner, Tex.: Tex. Res. Found.

Cruikshank, J.W. 1952. 10-year diameter growth of selected tree species in South Georgia. U.S. Dep. Agric. For. Serv., Note No. 20, 1p. Southeast For. Exp. Stn., Asheville, N.C.

Cruikshank, J.W. and J.F. McCormack. 1956. The distribution and volume of hickory timber. U.S. Dep. Agric. For. Serv., Hickory Task Force Rep. No. 5. 12 p. Southeast For. Exp. Stn., Asheville, N.C.

Dale, M.E. 1972. Growth and yield predictions for upland oak stands 10 years after initial thinning. U.S. Dep. Agric. For. Serv., Res. Pap. NE-241. 21 p.

Della-Bianca, L. 1975. A case for thinning yellow-poplar. South. Lumberman 231(2872):101-103.

Evans, T.F., H.E. Burkhart, and R.C. Parker. 1975. Site and yield information applicable to Virginia's hardwoods: a review. M.F. thesis. Va. Polytech. Inst. and State Univ., Blacksburg, Va. 143 p.

Fernald, M.L. 1950. Gray's manual of botany. 8th ed. 1632 p. New York, N.Y.: Am. Book Co.

Gingrich, S.F. 1971a. Management of young and intermediate stands of upland hardwoods. U.S. Dep. Agric. For. Serv., Res. Pap. NE-195. 26 p.

Gingrich, S.F. 1971b. Stocking, growth, and yield of oak stands. *In* Oak symp. proc., pp. 65-73. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Graney, D.L. and D.R. Bower. 1971. Site index curves for red and white oaks in the Boston Mountains of Arkansas. U.S. Dep. Agric. For. Serv., Res. Note. SO-121. 4 p.

Hampf, F.E. 1965. Site index curves for some forest species in the eastern United States. (Rev.) 43 p. U.S. Dep. Agric. For. Serv., East. Reg., Upper Darby, Pa.

Hare, R.C. 1976. Rooting of American and formosan sweetgum cuttings taken from girdled and nongirdled cuttings. U.S. Dep. Agric. For. Serv., Tree Plant. Notes 27(4):6-7,33.

Harlow, W.M. 1959. Fruit key and twig key to trees and shrubs. 106 p. New York, N.Y.: Dover Publ.

Harlow, W.M. and E.S. Harrar. 1941. Textbook of dendrology covering the important forest trees of the United States and Canada. 2nd ed. 542 p. New York, N.Y.: McGraw-Hill Book Co., Inc.

Harrar, E.S. and J.G. Harrar. 1962. Guide to southern trees. 2nd ed. 709 p. New York, N.Y.: Dover Publ., Inc.

Hedlund, A. and H.A. Knight. 1969. Hardwood distribution maps for the South. U.S. Dep. Agric. For. Serv., Resour. Bull. SO-19. 13 p.

Johnson, P.S. 1975. Growth and structural development of red oak sprout clumps. For. Sci. 21:413-418.

Johnson, R.L. 1971. Timing and planning for hardwood regeneration in the Coastal Plains. *In* Proc.—symp. on southeastern hardwoods, p. 44-49. U.S. Dep. Agric. For. Serv., State and Priv. For.

Judson, G.M. 1965. Tree diameter growth in Alabama. U.S. Dep. Agric. For. Serv., Res. Pap. SO-17. 3 p.

Kellison, R.C. 1967. A geographic variation study of yellow-poplar (*Liriodendron tulipifera* L.) within North Carolina. Tech. Rep. No. 33, 41 p. N.C. State Univ., Raleigh, N.C.

Kral, R. 1961. Sweetbay (*Magnolia virginiana* L.). *In* Deer browse plants of southern forests. USDA For. Serv. South. and Southeast. in coop. with the For. Game Res. Comm., Southeast. Sect. of the Wildlife Soc., p. 40-41.

Ledig, F.T., J.W. Beland, IV, and J.H. Fryer. 1971. Breeding techniques for white oak. *In* Proc. of the Eleventh Conf. on South. For. Tree Improv., p. 275-283.

Little, E.L., Jr. 1953. Check list of native and naturalized trees of the United States (including Alaska). U.S Dep. Agric., Agric., Handb. No. 41. 472 p. U.S. Gov. Print. Off., Washington, D.C.

Little, E.L., Jr. 1971. Atlas of the United States trees. Vol. 1. Conifers and important trees. U.S. Dep Agric., Misc. Publ. No. 1146. 320 p. U.S. Gov. Print. Off., Washington, D.C.

Lyle, E.S., Jr. 1973. Volume table for natural sweetgum in Alabama. Agric. Exp. Stn. Circ. 204, 8 p. Auburn Univ., Auburn, Ala.

Lyle, E.S., Jr., R.M. Patterson, D.R. Hicks, and E.L. Bradley. 1975. Polymorphic site index curves for natural sweetgum in Alabama. Agric. Exp. Stn. Circ. 220, 7 p. Auburn Univ., Auburn, Ala.

Manwiller, F.G. 1975. Wood and bark moisture contents of small-diameter hardwoods growing on southern pine sites. Wood Sci. 8:384-388.

McCarthy, E.F. 1933. Yellow poplar characteristics, growth and management. U.S. Dep. Agric. For. Serv., Tech. Bull. No. 356. 58 p.

McClurkin, D.C. 1963. Soil-site index predictions for white oak in North Mississippi and West Tennessee. For. Sci. 9:108-113.

McIntyre, A.C. 1933. Comparative radial growth of various oaks. J. For. 31: 341-342.

McKnight, J.S. 1958., Thinning stands of water oaks. *In* Management of bottomland forests, proc. of the seventh annu. for. symp., pp. 46-50. Sch. of For., La. State Univ.

Merz, R.W. and S.G. Boyce. 1956. Age of oak "seedlings." J. For. 54:774-775.

Mignery, A.L. 1975. Direct-seeding oaks on the Cumberland Plateau in Tennessee. U.S. Dep. Agric. For. Serv., Res. Pap. SO-107. 11 p.

Muller, C.H. 1951. The oaks of Texas. *In* Contributions from the Tx. Res. Found. 1(3):21-311. Dallas, Tx.: Ethridge Print. Co.

Nelson, T.C. 1965. Silvical characteristics of the commercial hickories. U.S. Dep. Agric. For. Serv., Hickory Task Force Rep. No. 10, 16 p. Southeast. For. Exp. Stn., Asheville, N.C.

Olson, D.F., Jr. and S.G. Boyce. 1971. Factors affecting acorn production and germination and early growth of seedlings and seedling sprouts. *In* Oak symp. proc., p. 44-48. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Preston, R.J., Jr. 1970. North American Trees. Rev., 395 p. Cambridge, Mass.: The M.I.T. Press.

Russell, T.E. 1971. Seeding and planting upland oaks. *In* Oak symp. proc., pp. 49-54. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Russell, T.E., N.S. Loftus, A.L. Mignery, and G.W. Smalley. 1970. Planting yellow-poplar in central Tennessee and northern Alabama. U.S. Dep. Agric. For. Serv., Res. Pap. SO-63. 17 p.

Russell, T.E. 1976. Evaluation of animal hazard to spot-seeded white ash in central Tennessee. U.S. Dep. Agric. For. Serv., Res. Note SO-213. 3 p.

Sargent, C.S. 1961. Manual of the trees of North America. 2nd. ed. 910 p., 2 vols. New York, N.Y.: Dover Publ., Inc.

Schlaegel, B.E., D.L. Kulow, and R.N. Baughman. 1969. Empirical yield tables for West Virginia yellow-poplar. W. Va. Univ. Agric. Exp. Stn. Bull. 574T, 24 p. Morgantown, W. Va.

Schnur, G.L. 1937. Yield, stand, and volume tables for even-aged upland oak forests. U.S. Dep. Agric. For. Serv., Tech. Bull. No. 560. 87 p.

Small, J.K. 1933. Manual of the southeastern flora. 1554 p. Lancaster, Pa.: The Sci. Press Print. Co.

Smalley, G.W. 1967. Soil-site relations of upland oaks in north Alabama. U.S. Dep. Agric. For. Serv., Res. Note SO-64. 6 p.

Smalley, G.W. 1969. Ten-year growth of yellow-poplar planted in North Alabama. J. of For. 67:567-568.

Smalley, G.W. 1973. Hackberry—an American wood. U.S. Dep. Agric. For. Serv., Leafl. No. FS-238. 7 p.

Smalley, G.W. and K. Pierce. 1972. Yellow-poplar, loblolly pine, and Virginia pine compared in Cumberland Plateau plantations. U.S. Dep. Agric. For. Serv., Res. Note SO-141. 6 p.

Southern Hardwood Lumber Manufacturers' Association. (n.d.a) Southern hardwood properties guide. 7 p. Memphis, Tenn.: South. Hardwood Lumber Manuf. Assoc.

Southern Hardwood Lumber Manufacturers' Association. (n.d.b) The southern hardwoods. 67 p. Memphis, Tenn.: South. Hardwood Lumber Manuf. Assoc.

Sprague, J. and R.J. Weir. 1973. Geographic variation of sweetgum. *In* Proc. of the twelfth south. for. tree improv. conf., pp. 169-180. Baton Rouge, La.

Stewart, H.A. and J.E. Krajicek. 1973. Ash—an American wood. U.S. Dep. Agric. For. Serv., Leafl. FS-216. 7 p.

Trimble, G.R., Jr. 1975. Summaries of some silvical characteristics of several Appalachian hardwood trees. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. NE-16. 5 p.

Trimble, G.R., Jr., and S. Weitzman. 1956. Site index studies of upland oak in the northern Appalachians. For. Sci. 2:162-173.

U.S. Department of Agriculture, Forest Service. 1965. Silvics of forest trees of the United States. U.S. Dep. Agric. For. Serv., Agric. Handb. 271. 762 p. U.S. Gov. Print. Off., Washington, D.C.

U.S. Department of Agriculture, Forest Service. 1974. Wood handbook: Wood as an engineering material. U.S. Dep. Agric. For. Serv., Agric. Handb. 72, rev. For. Prod. Lab., Madison, Wis.

U.S. Department of Agriculture, Forest Service. 1970. The silviculture of oaks and associated species. U.S. Dep. Agric. For. Serv., Res. Pap. NE-144. 66 p.

Vick, C.B. 1973. Yellow-poplar—an American wood. U.S. Dep. Agric. For. Serv., Leafl. FS-272. 7 p.

Vines, R.A. 1960. Trees, shrubs, and woody vines of the southwest. 1104 p. Austin, Tex.: Univ. of Tex. Press.

Watt, R.F., K.A. Brinkman, and B.A. Roach. 1973. Oak—hickory. *In* Silvicultural systems for the major forest types of the United States, p. 66-69. U.S. Dep. Agric. For. Serv., Agric. Handb. 445. U.S. Gov. Print. Off., Washington, D.C.

Webb, C.D. 1970. Genetics and tree improvement in the oak—yellow poplar type. *In* The silviculture of oaks and associated species, pp. 57-65. U.S. Dep. Agric. For. Serv., Res. Pap. NE-144.

Wharton, M.E. and R.W. Barbour. 1973. Trees and shrubs of Kentucky. 582 p. Lexington, Ky.: Univ. Press of Ky.

Wiant, H. V., Jr., M.A. Ramirez, and J.E. Barnard. 1975. Predicting oak site index by species composition in West Virginia. J. of For. 73:666-667.

Woods, F.W. and J.T. Cassady. 1961. Sprouting of sandhills scrub oaks following cutting. *In* Hardwood sprout development on cleared sites, pp. 7-8. U.S. Dep. Agric. For. Serv., Occas. Pap. 186. South. For. Exp. Stn., New Orleans, La.

Yawney, H.W. 1964. Oak site index on Belmont limestone soils in the Allegheny Mountains of West Virginia. U.S. Dep. Agric. For. Serv., Res. Pap. NE-30. 15 p.

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PART II— CHARACTERIZATION OF WOOD

Chapter	*Title*
4	PHYSIOLOGY
5	ANATOMY
6	CHEMICAL CONSITUENTS
7	SPECIFIC GRAVITY
8	WOOD-WATER RELATIONSHIPS
9	PHYSICAL PROPERTIES
10	MECHANICAL PROPERTIES
11	ATTACK BY PLANT ORGANISMS AND INSECTS
12	DEFECTS AND GRADES OF TREES AND LOGS

4

Physiology

This chapter, with some editorial changes and additions, it taken from D.D. Hook's (1977) review of the eco-physiology of hardwood species associated with southern pines, by permission of the author and Clemson University.

CHAPTER 4

Physiology

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CHAPTER 4

Physiology[1]

In trees of the temperate zone, wood formation centers around seasonal activity of the vascular cambium and the differentiation of its derivatives. The **cambium** may be viewed as a thin cylinder of generative cells surrounding the woody portion of the stem and protected by layers of inner and outer bark. Each growing season the cambium forms a layer of wood, and a layer of bark that is one-tenth to one-sixth as thick as the layer of wood. Most of the wood cells (**xylem**) become thick-walled and lignified; each new layer of inner bark (**phloem**) pushes the older, nonfunctional phloem outward as the stem enlarges. Successive **cork cambia** are formed in the older portion of the inner bark to produce outer layers of impervious cells that protect the phloem. Tissue outside the cork cambia die, and eventually are sloughed off. The activity of the cork cambium gives trees their characteristic bark patterns. (See chapter 13 for a more complete description of bark anatomy.)

Water from tree roots is conducted upward through the outer portion of the woody cylinder by tensions created in the crown, and is distributed to the cambial and other living cells by osmotic forces. Food in the form of sugar, synthesized in the leaves, is transported through the living inner bark (**functional phloem**) to the cambium, where cell divisions are taking place. Sugars are also conducted radially and stored, mostly as starch, in the horizontal rays.

Developmental events in the tree crown greatly affect cambial activity, differentiation of xylem derivatives, and formation of wood along the bole. For illustrated discussions of the physical nature of the vascular cambium, the mechanics of cell division, cambial origin, activation of the cambium, and production, differentiation, and maturation of cells, see Kramer and Kozlowski (1960), Esau (1965), Muhlethaler (1965), Wardrop (1965), Zasada and Zahner (1969), Zimmerman and Brown (1971), and Berlyn (1979).

Structure of the mature material, rather than phases of its development, is of most interest to wood technologists and hardwood users. Such readers will find detailed descriptions of the anatomy of wood in chapter 5; chapter 13 describes the anatomy of inner and outer bark, while chapters 14 and 15 illustrate the anatomy of roots and foliage.

Resource managers responsible for silviculture and harvesting of hardwoods on pine sites must be concerned with growth relationships, stem form, and effects on tree development of environmental factors such as light, moisture, and nutrients, modes of regeneration, and genetic variability. The bulk of this chapter is therefore devoted to these subjects.

Because literature describing hardwoods on southern pine sites is scarce, some observations on hardwoods growing elsewhere are included as approximations, or to help identify needs for future research.

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[1] See acknowledgement on chapter front page.

4-1 TREE FORM AND GROWTH

Stem form and diameter class largely determine the utility of a hardwood tree. Demand is greatest for large-diameter trees with long straight boles. Today such trees are scarce on southern pine sites because of site limitations, past harvesting practices, and the nature of the species.

In five of the 23 hardwood species, or species groups associated with southern pines (table 4-1), i.e., sweetgum, black tupelo, yellow-poplar, sweetbay, and sugarberry, growth form is typically **excurrent;** these species tend to have an undivided central stem (see fig. 3-56). Sixteen (the oaks, hickories, elms, and red maple) frequently have forked stems typical of **deliquescent** or **decurrent** form of growth (see fig. 3-35); the two ash species are intermediate (Zimmerman and Brown 1971).

Obviously, excurrent growth form favors development of long, straight boles. Some research suggests that growth form is also associated with seasonal timing of growth. Kramer (1943) found that white ash, red oak, and white oak in North Carolina, all species with decurrent form, made 50 percent of their height growth by May 1, with a total growth period of 130-135 days. Yellow-poplar, a species with excurrent growth form, grew at a more consistent rate through a 160-day period. In Missouri, the height growth of black ash (*Fraxinus nigra* Marsh.), white oak and post oak was completed in a 19 day period in the spring but shortleaf pine height growth continued from April to September (Johnston 1941).

Kozlowski and Ward (1957) state that timing of height growth of deciduous species is controlled primarily by hereditary factors; Kramer (1943) noted that in North Carolina seedlings of white ash and yellow-poplar from northern seed sources began growth later and ceased growth earlier in the fall than seedlings of the same species from a southern seed source. Heredity also affects height growth, but moisture may be equally important. Tryon et al. (1957) found that early-season precipitation influenced annual height increment of yellow-poplar in West Virginia. Since, in the South, moisture is usually plentiful in the spring, height growth of species which complete growth early is little affected by summer drought; moisture deficiency in summer reduces both height and diameter growth of species with extended growing seasons.

Kramer and Kozlowski (1960) note that diameter growth of hardwoods appears to be more affected by environmental factors than height growth. This observation is supported by findings that early-season precipitation is more closely related to diameter growth of yellow-poplar in West Virginia than to height growth (Tryon et al. 1957).

As is the case with height growth, duration of radial growth of hardwoods in the South varies substantially among species. For example, in the Piedmont of Georgia, 50 percent of total radial growth was achieved by winged elm and sweetgum in 40 to 49 days, post oak and red maple in 50-59 days, southern red oak in 60 to 69 days, white oak and yellow-poplar in 70 to 79 days and mockernut hickory in 100 to 109 days (Jackson 1952).

TABLE 4-1.—*Three silvical traits of hardwood species growing on southern pine sites*

Species	Tolerance[1]	Growth form[2]	Drought resistance[3]
Ash, green	Mod		
Ash, white	Mod		
Elm, American	Tol	D	Intol
Elm, winged		D	
Hackberry, spp	Mod	E	Intol
Hickory, spp	Mod	D	Mod-to-Tol
Maple, red	Tol	D	
Oak, black	Mod	D	Intol
Oak, blackjack	Intol	D	Very Tol
Oak, cherrybark	Intol to Mod	D	
Oak, chestnut	Mod	D	Tol
Oak, laurel	Mod	D	
Oak, northern red	Tol	D	Intol
Oak, post	Intol	D	Very Tol
Oak, scarlet	Intol	D	Intol to Mod
Oak, Shumard	Intol to Mod	D	
Oak, southern red	Mod	D	
Oak, water	Intol to Mod	D	
Oak, white	Mod	D	Mod to Tol
Sweetbay	Mod	E	
Sweetgum	Intol	E	
Tupelo, black	Tol	E	
Yellow-poplar	Intol	E	

[1] Tolerance classifications are derived from Fowells (1965), Bourdeau (1954), and Baker (1950). Tolerant trees can develop in shade; intolerant trees demand full light for optimum development. Moderately tolerant trees are intermediate in light requirement.

[2] Growth form summarized from Zimmerman and Brown (1971). E denotes excurrent and D indicates decurrent.

[3] Drought resistence summarized from Seidel (1972), Parker (1969), and Bourdeau (1954).

4-2 LIGHT

The ability of young hardwoods to stay alive under a pine overstory is a measure of their **tolerance** and is a principle key to their survival and ultimate dominance on pine sites. Although factors other than light are involved (Decker 1955), the tolerance classification of a species is a farily accurate index to its light requirement.

Seventeen of the hardwood species that are important on pine sites are classified as tolerant or intermediate in tolerance; only eight (yellow-poplar, sweetgum, and blackjack, cherrybark, post, scarlet, Shumard, and water oaks) are classified as intolerant (table 4-1).

It is likely that tolerance of hardwoods is closely related to leaf stomata response to changes in light intensity. Supporting this concept, a study of four hardwood species showed that stomata of tolerant species opened and closed more quickly in response to changes in light intensity than did those of intolerant species (Woods and Turner 1971).

A few evaluations applicable to pine-site hardwoods have been published. Whereas loblolly pine seedlings require full sunlight for maximum photosynthesis, white oak, red maple, and yellow-poplar reach maximum rates at one-third sunlight or less (Kramer and Decker 1944, Kozlowski 1949). Other studies have shown that light intensity is not a critical factor in the survival and growth of many hardwoods under a variety of field conditions (Ferrell 1953). Bourdeau (1954) found that northern red oak responded in a manner similar to the hardwood species tested by Kramer and Decker (1944) and Kozlowski (1949), but blackjack oak reached maximum photosynthetic rate at about 8,500 foot candles, i.e., 85 percent full light. Phares (1971) found that northern red oak seedlings attained maximum dry weight accumulation under 100 percent full light, maximum height growth with 30 percent full light, and minimum height and weight growth with 10 percent full light. Farmer (1974) also found that northern red oak seedlings made best growth in 100 percent full light if the day-night temperature regimes were 23° to 23°C or 29° to 23°C. Under such conditions, the seedlings made 4 to 5 growth flushes in a 4-month period.

Foliar characteristics can affect the intensity and color of penetrating light. The natural shading characteristic of pine foliage arrangement is apparently responsible for the higher light intensity requirements of pines compared to hardwoods (Kramer and Clark 1947). Light penetrating the hardwood forest canopy is low in blue and high in yellow and green wavelengths; under conifer canopies the color of sunlight is little changed, but the intensity is substantially reduced (Toumey 1937).

Hardwood species have a more pronounced **phototropic response** to light than conifer species. This tendency of hardwoods to turn toward the light frequently results in crooked stems and irregular crowns in response to indirect light sources under an overstory (Smith 1962, Zimmerman and Brown 1971).

Seasonal development of northern red oak and scarlet oak seedlings is affected by canopy cover during the previous growing season. Seedlings of both species grown under a forest canopy broke terminal bud dormancy nine days earlier than seedlings grown in open fields regardless of canopy cover at the time of budbreak. Thus harvest removal of the canopy cover during the dormant season can expose seedlings of these species to serious spring frost damage. Where the canopy remains intact, however, the seedlings may gain 9 to 15 days growth advantage at a critical time before overstory hardwoods leaf out. Such a small advantage could be critical to the survival of the seedlings in the understory (McGee 1975, 1976).

4-3 MOISTURE

Soil moisture is a limiting factor for maximum growth of pines in the upland pine-hardwood stands in the South (Grano 1970). Water may be lost from such sites 25 percent faster in pine stands with dense hardwood understories than in pine stands with hardwood understories removed (Zahner 1958). Because soil moisture is limiting, differences in **drought resistance** among the various hardwood species (table 4-1) is undoubtedly a critical factor in their distribution and growth on the pine sites.

Bourdeau (1954) concluded from his studies on the ecology of oak seedlings that poor-site species (post oak and blackjack oak) are unsuccessful on good sites because of shade intolerance and inherent slow growth, and that good-site species (northern red oak, scarlet oak, and white oak) are eliminated from poorer sites because of insufficient drought resistance. Thus, dying of scarlet oak on poor sites in West Virginia was attributed to rainfall deficiencies (Tryon and True 1958).

Among hickory species, pignut hickory is usually the most drought resistant (Parker 1969).

In laboratory studies of mature leaves from seedlings, Wuenscher and Kozlowski (1971) found that differences in resistance to water loss among five hardwood species were correlated with their distribution along an ecological gradient from **xeric** (dry) to **mesic** (moist) site adaptation. Under most test conditions, resistance was highest for black oak, followed in declining order by northern red, white, and bur oak (*Quercus macrocarpa* Michx.), and was least for sugar maple (*Acer saccharum* Marsh.). Resistance increased with increasing leaf temperature and decreased with increasing light intensity; the latter trend was presumed to be caused by light-induced opening of stomata.

Carpenter and Smith (1974) reported that mesic species among the southern Appalachian hardwoods of Kentucky had fewer stomata per unit leaf area than xeric species.

In a laboratory study of leaves of four oaks, Seidel (1972) found that post oak was most drought resistant, northern red oak least resistant and black oak and white oak moderate in resistance. Northern red oak showed least ability to avoid drought by reducing transpiration, but all showed similar reductions in transpiration rate with soil water potentials of −25 bars. Reductions in all four species were attributed to stomatal closure. The greater drought resistance of post oak resulted from inherent properties of the protoplasm which permitted dehydrated tissues of roots and leaves to recover. Northern red oak was least drought resistant primarily because of its low drought avoidance characteristics.

In studying the distribution of post, blackjack and black oaks, and black hickory (*Carya texana* Buckl.) in Oklahoma, Johnson and Risser (1972) found by ordination and multiple regression analysis that distribution of post oak and black hickory was correlated to relatively high levels of moisture, and blackjack oak to drier sites. Black oak is favored by relatively moist conditions, but tolerates low nutrient levels. Although limited to data from Oklahoma, this study should apply to pine sites in the post oak region of Texas.

At comparable levels of declining soil moisture, the apparent photosynthetic rate of loblolly pine seedlings is reduced more than that of oak seedlings (Kozlowski 1949 and Bormann 1953).

4-4 NUTRIENTS

Information on nutrient requirements of upland hardwoods is scarce. Available data suggest that interactions among many factors must be taken into account for meaningful interpretation of experimental observations. Following are limited data related to fertilization with nitrogen (N), phosphorous (P), potassium (K), calcium (Ca), and magnesium (Mg).

Fertilization studies in pine and mixed hardwood stands in the Tennessee Valley showed that the hardwoods responded slightly more to N and N + P treatments than pines. Yellow-poplar, the fastest growing hardwood, had greater response than any other species treated but treatment effect decreased after one year. Red oaks, the second fastest growing group responded less than the other species. White oaks and hickories responded slightly less than yellow-poplar. Soil moisture was considered to be one of the most important but unevaluated variables in interpreting site differences (Farmer et al. 1970).

In Pennsylvania, N treatments increased diameter increment of white and scarlet oaks. Additions of Ca at 1000 lbs. per acre resulted in increased diameter growth of both species but P had no measurable influence (Ward and Bowersox 1970). Auchmoody (1972) showed that red oak seedlings in pot studies responded well to N + P and N + P + K but P and K alone or in combination did not influence growth. He suggested further study of nutrient interactions for better interpretations of field trials. In controlled experiments, Phares (1971) found that red oak seedlings did not respond to NPK treatments when grown under less than 30 pecent full light.

Pot studies with first year seedlings of white ash using different concentrations and combinations of N, P, K, Ca, and Mg showed that only N had a measurable effect on anatomical features. Level of N was negatively correlated with vessel segment length and percentage of fibers; it was positively correlated with percentage of ray tissues (Foulger et al. 1972).

4-5 VEGETATIVE REGENERATION

Species composition on southern pine sites is much affected by the inability of most pines to sprout from stumps or roots, and the ability of most of the hardwood species listed in table 4-1 to regenerate readily by stump sprouts. Some of the species—particularly sweetgum—regenerate by both stump and root sprouts (Putnam et al. 1960, Kormanik and Brown 1967b). Sprouting characteristics are affected by stump height and diameter, by season of cutting, and by site.

Studies on several oak species over three decades show that large stumps do not sprout prolifically and that survival of such sprouts is poor. Sprouts on stumps less than 12 inches in diameter are more vigorous and have less decay if they originate on the stump less than one inch above the soil surface (Roth and Hepting 1969).

In a study of 80 overtopped white oaks felled during winter and examined the following growing season, McGee (1978) found that 62 of the stumps produced a total of 1,086 sprouts; removal of the overtopping hardwoods had little effect on whether or not the stump sprouted or on numbers or heights of sprouts. The tallest sprout on each stump averaged 2.5 ft. Maximum sprouting came from trees about age 40, with a gradual decline to age 60; beyond age 60 only 1 of 10 trees produced stump sprouts. Almost all sprouts grew from below the groundline of the stump.

Studies by DeBell (1971) and Hook and DeBell (1970) showed most prolific sprouting from higher stumps of water tupelo (*Nyssa aquatica* L.) and swamp tupelo (*N. sylvatica* var *biflora* Walt. (Sarge.)), but provided no specific information on typical black tupelo, which is the important species of this genus on pine sites.

Multiple-stem sprouts of red oak and yellow-poplar in West Virginia gave the same site index as single stems of the same species when they were in dominant or codominant positions in the stands (Trimble 1968, Kulow and Tryon 1968).

In reviewing the literature on sprouting of hardwoods, Wenger (1953) reported that good sites resulted in more vigorous sprouts, sprouting incidence increased with size of parent tree up to five inches dbh then decreased, sprouting incidence was least from trees cut during the active growth period and highest in those cut while dormant and that seasonal variation in sprouting appeared to be related to seasonal carbohydrate fluctuations. However, for small sweetgum trees ($\bar{<}$ 3 inches dbh), he found no correlation between season of cutting or carbohydrate fluctuation and the numbers or heights of sprouts; size of average sprout, however, was correlated with time of cutting, being least at first full leaf and in the late summer. Number and size of sprouts increased with stump diameter.

Hook and DeBell (1970) were unable to correlate season of sprouting and carbohydrate content of stem and root tissue on swamp and water tupelo with high stumps (6 inches tall) but a definite correlation existed between seasonal sprouting and carbohydrate content of root tissue from low stumps (< ½ inches). Stem carbohydrate content in high stumps appeared to be sufficient to support vigorous sprouting throughout the season, but root carbohydrate content dropped to essentially zero during active growth. Presumably sprouting on low stumps was dependent upon the carbohydrate reserves of the root tissue for sprout initiation and development.

There is considerable evidence that many sweetgum stands originate from sprouts and that root sprouting is more prolific on upland sites (Johnson 1964). Kormanik and Brown (1967b) found extensive root sprout clumps in the Piedmont of Georgia. When the root systems of sprouts in the Piedmont were compared to root systems of sprouts in the Coastal Plain of South Carolina, it was found that secondary roots developed more prolifically in the Coastal Plain (Hook et al. 1970). The propensity of sweetgum to regenerate by root sprouts and inadequate secondary root development on certain sites may contribute to the problem of sweetgum blight during extended droughts.

4-6 FACTORS AFFECTING QUALITY

For best growth, most of the hardwood species require more moisture and more fertile soils than are provided by typical southern pine sites. Readers interested in a method of site evaulation for important southern hardwoods, including green ash, hackberry, sugarberry, sweetgum, yellow-poplar, and Shumard, cherrybark, and water oaks, will find useful the technique described by Baker and Broadfoot (1979).

Stresses from growth on typical southern pine sites slow growth of hardwoods and increase their susceptibility to attacks by insects and disease. The effects of these attacks are discussed in detail in chapters 11 and 12, but some general comments seem in order.

The oaks are particularly susceptible to heart rot following fire injury (Toole and Furnival 1957). Oak species decay much faster after fire injury in the South than in the North, due apparently to climate and presence of suitable fungi (Hepting and Shigo 1972). Several diseases of southern hardwoods appear to be aggravated by adverse site and climate conditions (Powers 1963). Sweetgum blight, which was prevalent throughout the South in the early 1950's, appeared to be related to drought conditions (Toole 1959).

With intensive forestry, disease problems tend to shift from heart rot and other diseases of old age to root rots, stem cankers, foliage disease and physiogenic disorders. Insects attacking shoots and leaders, defoliaters, sucking insects, and inner bark and cambium feeders also assume greater importance (Shea 1971).

Silvicultural manipulations or other disturbances that alter the physiological balance of the tree may cause **epicormic** branches (sprouts) to develop in hardwoods with consequent degrade of logs (Kramer and Kozlowski 1960, Zimmerman and Brown 1971). Epicormic branches arise from suppressed buds in the bark; these may be accessory buds, connected by trace tissues to the pith, or adventitious buds originating abnormally in other tissues. On yellow-poplar, sweetgum, green ash and red maple epicormic branches from adventitious buds are uncommon and short-lived; they result in little defect in these species. In white and water oak, 30 percent of epicormic branches may be from such buds, giving rise to serious defect (Kormanik and Brown 1967b).

In a study of sweetgum, Kormanik and Brown (1969) determined that suppressed buds at the base of lateral branches repeatedly subdivide long after the branches are lost through natural pruning, producing large numbers of suppressed buds in the inner and outer bark. They found these to be more numerous per unit area in large, than in small trees, and they could be stimulated to form short shoots or epicormic branches by pruning, girdling, or release of the tree from competition.

4-7 GENETIC VARIABILITY

Research on the genetic variability of southern hardwoods is very limited and, for the most part, has been conducted since 1958. In provenance tests of oak species at the Morris Arboretum in Philadelphia, Pennsylvania, water oak, Shumard oak, and bur oak were found to be quite variable in winter hardiness, growth rate, frost hardiness and autumn leaf coloration. Northern red oak, white oak, blackjack oak and post oak were less variable but showed significant differences in the same traits. Variation in northern red oak showed a geographic trend but white oak had as much variation within a locality as among different localities (Wright 1958).

One-year-old sweetgum seedlings from diverse seed sources (Mexico to New Jersey) showed differences in fiber tracheid length and specific gravity of wood when grown under a uniform environment. Tracheids were longest for the Mexican seed source and shortest for the most northern seed source. Specific gravity of wood was greatest in trees grown from seeds originating in more northerly latitudes. There possibly was a relationship between fiber tracheid length, cell diameter and latitude of origin (Winstead 1972). Williams (1971ab) found ecotypic responses in sweetgum seedlings in the Hill reaction and in levels of soluble sugars and adenosinetriphosphate; seedlings analyzed came from the extremities of the range of sweetgum in the Western Hemisphere.

Specific gravity of yellow-poplar wood from Virginia, North Carolina, and Georgia sources decreased with increasing elevation and more northerly latitudes. Although some variability was related to environmental factors, much of the tree-to-tree and about half of the plot-to-plot variations in specific gravity were due to genetic variation (Sluder 1972).

A study of variation in white oak in the Southern Appalachians indicated the genotype was highly plastic, but no ecotypes were found (Baranski 1975). Leaf morphology was sensitive to heat energy within the crown. Greater lobing and deeper sinuses were associated with hotter and dryer climates; similar variation could be found within the crown from the center outward in response to microclimate changes.

Differences were found in the content of fats, phenols, isoenzymes and pigments of red maple from New York to Florida, indicating racial differences in dormancy patterns, cold tolerance and chilling injury (Perry 1971). Ecotypic variability in root respiration rate was found within red maple and yellow-poplar sources as well as between species (Steinbeck and McAlpine 1966).

Future genetic research on the upland hardwoods should concentrate on exploring ecotypic variability in light, moisture, and nutrient requirements and in vegetative regenerative potentials. Proven ecotypes could be exploited in major breeding programs already in progress throughout the South.

4-8 LITERATURE CITED

Auchmoody, L.R. 1972. Effects of fertilizer-nutrient interactions on red oak seedling growth. USDA For. Serv. Res. Pap. NE-239, 5 p. Northeast. For. Exp. Stn., Upper Darby, Pa.

Baker, F.S. 1950. Principles of silviculture. 414 p. New York, N.Y.: McGraw-Hill Book Co., Inc.

Baker, J.B., and W.M. Broadfoot. 1979. Site evaluation for commercially important southern hardwoods. Gen. Tech. Rep. SO-26, U.S. Dep. Agric., For. Serv. 51 p.

Baranski, M.J. 1975. An analysis of variation within white oak (*Quercus alba* L.). N.C. Agric. Exp. Stn. Tech. Bull. No. 236, 176 p. N.C. State Univ., Raleigh, N.C.

Berlyn, G.P. 1979. Physiological control of differentiation of xylem elements. Wood and Fiber 11:109-126.

Bormann, F.H. 1953. Factors determining the role of loblolly pine and sweetgum in early old-field succession in the Piedmont of North Carolina. Ecol. Monogr. 23(4):339-358.

Bourdeau, P. 1954. Oak seedling ecology determining segregation of species in Piedmont oak-hickory forests. Ecol. Monogr. 24:297-320.

Carpenter, S.B. and N.D. Smith. 1974. A scanning electron microscope study of stomata and cuticular surfaces of southern Appalachian hardwoods. (Abstr.) *In* Proc. of the third North Am. For. Biol. Workshop, p. 361. C.P.P. Reid and G.H. Fechner, eds. Fort Collins, Colo. State Univ.

DeBell, D.S. 1971. Stump sprouting after harvest cutting in swamp tupelo. USDA For. Serv. Res. Pap. SE-83, 6 p. Southeast. For. Exp. Stn., Asheville, N.C.

Decker, J.P. 1955. The uncommon denominator in photosynthesis as related to tolerance. For. Sci. 1:88-89.

Esau, K. 1965. On the anatomy of the woody plant. *In* Cellular ultrastructure of woody plants, pp. 35-50. W.A. Côté, Jr., ed. Syracuse, N.Y.: Syracuse Univ. Press.

Farmer, R.E., Jr. 1974. Growth analysis of juvenile northern red oak. (Abstr.) *In* Proc. of the third North Am. For. Biol. Workshop, p. 369. C.P.P. Reid and G.H. Fechner, eds. Fort Collins, Colo.: Colo. State Univ.

Farmer, R.E., Jr., G.W. Bengtson, and J.W. Curlin. 1970. Response of pine and mixed hardwood stands in the Tennessee Valley to nitrogen and phosphorus fertilization. For. Sci. 16:130-136.

Ferrell, W.K. 1953. Effect of enviromental conditions on survival and growth of forest tree seedlings under field conditions in the Piedmont Region of North Carolina. Ecol. 34:667-688.

Foulger, A.N., F. Freese, and J. Harris. 1972. Effect of nutrient concentration on the stem anatomy of white ash seedlings. Wood and Fiber 4:112-114.

Foweils, H.A. 1965. Silvics of forest trees of the United States. U.S. Dep. Agric. For. Serv., Agric. Handb. 271. 762 p. U.S. Govt. Print. Off., Washington, D.C.

Grano, C.X. 1970. Small hardwoods reduce growth of pine overstory. U.S. Dep. Agric. For. Serv., Res. Pap. SO-55. 9 p.

Hepting, H.G. and A.L. Shigo. 1972. Difference in decay rate following fire beween oaks in North Carolina and Maine. Plant Dis. Rep. 56(5):406-407.

Hook, D.D. 1977. Eco-physiology of hardwood species associated with southern pines—a review. Clemson Univ. Dep. of For. Tech. Pap. No. 6, 17 p. Clemson, S.C.: Clemson Univ.

Hook, D.D. and D.S. DeBell. 1970. Factors influencing stump sprouting of swamp and water tupelo seedlings. U.S. Dep. Agric. For. Serv., Res. Pap. SE-57. 9 p.

Hook D.D., P.P. Kormanik, and C.L. Brown. 1970. Early development of sweetgum root sprouts in coastal South Carolina. U.S. Dep. Agric. For. Serv., Res. Pap. SE-62. 6 p.

Jackson, L.W.R. 1952. Radial growth of forest trees in the Georgia Piedmont. Ecol. 33:336-341.

Johnson, F.L. and P.G. Risser. 1972. Some vegetation-environment relationships in the upland forests of Oklahoma. J. Ecol. 60(3):655-663.

Johnson, R.L. 1964. Coppice regeneration of sweetgum. J. For. 62:34-35.

Johnston, J.P. 1941. Height-growth periods of oak and pine reproduction in the Missouri Ozarks. J. For. 39:67-68.

Kormanik, P.P. and C.L. Brown. 1967b. Root buds and the development of root suckers in sweetgum. For. Sci. 13:338-345.

Kormanik, P.P. and C.L. Brown. 1969. Origin and development of epicormic branches in sweetgum. U.S. Dep. Agric. For. Serv., Res. Pap. SE-54. 17 p.

Kozlowski, T.T. and R.C. Ward. 1957. Seasonal height growth of deciduous trees. For. Sci. 3:168-174.

Kramer, P.J. 1943. Amount and duration of growth of various species of tree seedlings. Plant Physiol 18:239-251.

Kramer, P.J. and W.A. Clark. 1947. A comparison of photosynthesis in individual pine needles and entire seedlings at various light intensities. Plant Physiol. 22:51-57.

Kramer, P.J. and J.P. Decker. 1944. Relation between light intensity and rate of photosynthesis of loblolly pine and certain hardwoods. Plant Physiol. 19:350-358.

Kozlowski, T.T. 1949. Light and water in relation to growth and competition of Piedmont forest tree species. Ecol. Monogr. 19:207-231.

Kramer, P.J. and T.T. Kozlowski. 1960. Physiology of trees. 642 p. New York, N.Y.: McGraw-Hill Book Co., Inc.

Kulow, D.L. and E.H. Tryon. 1968. Yellow-poplar twins reliable for determining site index. J. of For. 66:198.

McGee, C.E. 1975. Change in forest canopy affects phenology and development of northern red and scarlet oak seedlings. For. Sci. 21:175-179.

McGee, C.E. 1976. Differences in budbreak between shade-grown and open-grown oak seedlings. For. Sci. 22:484-486.

McGee, C.E. 1978. Size and age of tree affect white oak stump sprouting. U.S. Dep. Agric. For. Serv., Res. Note SO-239. 2 p.

Mühlethaler, K. 1965. Growth theories and the development of the cell wall. *In* Cellular ultrastructure of woody plants, pp. 51-60. W.A. Côté, ed. Syracuse, N.Y.: Syracuse Univ. Press.

Parker, J. 1969. Further studies of drought resistance in woody plants. The Bot. Rev. 35(4):317-371.

Perry, T.O. 1971. Seasonal and genetic differences in fats, phenols, isoenzymes, and pigments of red maple. For. Sci. 17:209-212.

Phares, R.E. 1971. Growth of red oak (*Quercus rubra* L.) seedlings in relation to light and nutrients. Ecol. 52:669-672.

Powers, H.R., Jr. 1963. Disease and hardwood management. For. Farmer. 23(1):15, 32-35.

Putnam, J.A., G.M. Furnival, and J.S. McKnight. 1960. Management and inventory of southern hardwoods. U.S. Dep. Agric. For. Serv., Agric. Handb. 181. 102 p. U.S. Govt. Print. Off., Washington, D.C.

Roth, E.R. and G.H. Hepting. 1969. Prediction of butt rot in newly regenerated sprout oak stands. J. For. 67:756-760.

Seidel, K.W. 1972. Drought resistance and internal water balance of oak seedlings. For. Sci. 18(1):34-40.

Shea, K.R. 1971. Disease and insect activity in relation to intensive culture of forests. Int. Union For. Org. Cong. proc., pp. 109-118. Gainvesville, Fla.

Sluder, E.R. 1972. Variation in specific gravity of yellow-poplar in the southern Appalachians. Wood Sci. 5:132-138.

Smith, D.M. 1962. The practice of silviculture. 7th ed. 578 p. New York, N.Y.: John Wiley & Sons, Inc.

Steinbeck, K. and R.G. McAlpine. 1966. Inter- and intra-specific differences in the root respiration rates of four hardwood species. For. Sci. 12:473-476.

Toole, E.R. 1959. Sweetgum blight. U.S. Dep. Agric. For. Serv., For. Pest Leafl. 37. 4 p.

Toole, R.E. and G.M. Furnival. 1957. Progress of heart rot following fire in bottomland red oaks. J. For. 55:20-24.

Toumey, J.W. 1937. Foundations of silviculture upon an ecological basis, revised by C.F. Korstian. 2nd ed. New York, N.Y.: John Wiley & Sons, Inc.

Trimble, G.R. 1968. Multiple stems and single stems for red oak give same site index. J. For. 66:198.

Tryon, E.H., J.O. Cantrell, and K.L. Carvell. 1957. Effect of precipitation and temperature on increment of yellow-poplar. For. Sci. 3:32-44.

Tryon, E.H. and R.P. True. 1958. Recent reductions in annual radial increments in dying scarlet oaks related to rainfall deficiencies. For. Sci. 4:219-230.

Ward, W.W. and T.W. Bowersox. 1970. Upland oak response to fertilization with nitrogen, phosphorus, and calcium. For. Sci. 16:113-120.

Wardrop, A.B. 1965. Cellular differentiation in xylem. *In* Cellular ultrastructure of woody plants, pp. 61-97. W.A. Côté, ed. Syracuse, N.Y.: Syracuse Univ. Press.

Wenger, K.F. 1953. The sprouting of sweetgum in relation to season of cutting and carbohydrate content. Plant Physiol. 28:35-49.

Williams, G.J. III. 1971a. Levels of soluble sugars and ATP in ecotypes of *Liquidambar styraciflua* L. Photosynth. 5(4):399-405.

Williams, G.J., III. 1971. Populational differentiation in the hill reaction of United States, Mexico, and Central America *Liquidambar styraciflua* L. Photosynth. 5(3):139-145.

Winstead, J.E. 1972. Fiber tracheid length and wood specific gravity of seedlings as ecotypic characters in *Liquidambar styraciflua* L. Ecol. 53(1):165-172.

Woods, D.B. and N.C. Turner. 1971. Stomatal response to changing light by four tree species of varying shade tolerance. New Phytol. 70:77-84.

Wright, J.W. 1958. Possibilities of genetic improvement of the southern bottomland hardwoods. *In* Management of bottomland forests, proc. of the seventh annu. for. symp., pp 27-34. Baton Rouge, La.: La. State Univ.

Wuenscher, J.E. and T.T. Kozlowski. 1971. Relationship of gas-exchange resistance to tree-seedling ecology. Ecol. 52(6):1016-1023.

Zahner, R., 1958. Hardwood understory depletes soil water in pine stands. For. Sci. 4:178-184.

Zasada, J.C. and R. Zahner. 1969. Vessel element development in the earlywood of red oak (*Quercus rubra*). Can. J. of Bot. 47:1965-1971.

Zimmerman, M.H. and C.L. Brown. 1971. Trees structure and function. 336 p. New York, N.Y.: Springer Verlag New York Inc.

5

Anatomy

This chapter is the result of cooperation among several scientists. It is based on a literature search, outline, and first draft written by P. Koch. W.A. Côté and his associates at the N.C. Brown Center for Ultrastructure Studies provided most of the micrographs. The color illustrations were provided by C.W. McMillin and Paul Szopa. F.W. Manwiller's characterization data are the basis for many of the tables. Information on heartwood formation was condensed from research by A.L. Shigo and W.E. Hillis. The numerous contributions were supplemented by data from the files of H.A. Core who unified the various contributions and assembled the illustrations.

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CHAPTER 5

Anatomy

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CHAPTER 5

Anatomy[1]

In evaluation of hardwoods as industrial raw materials, two aspects of their anatomy are of major importance. First, hardwood fibers are only about one-third the length (1 to 2 mm) of softwood fibers (about 4 mm in the major southern pines). Second, their structure is more complex than that of southern pine and other softwoods, in that they have more types of cells, and the cells are not arranged in radial alignment as is typical of softwoods.

Anatomical variations among hardwood species significantly affect the physical and mechanical properties of their wood, and hence their utilization. Because of these variations, hardwood species growing among southern pines can—with a few notable exceptions—be distinguished by anatomical features of their stemwood. An identification key is included at the end of this chapter (sect. 5-11), and an atlas of anatomical detail is presented in figures 5-4 through 5-15 and 5-22 through 5-45.

5-1 GROSS FEATURES

A wedge cut from an oak stem illustrates some of the features visible with the naked eye (figs. 5-1 and 5-2). Gross anatomical features helpful in species identification include: pith; bark characteristics (see chapters 3 and 13); distinctness of growth rings; vessel size; tissue groupings, distribution, and arrangement; parenchyma patterns; ray patterns; sapwood and heartwood; and figure.

Additionally, color of heartwood (see figures 5-4 through 5-16 and chapter 9), weight (see chapter 7) and hardness (see chapter 10) are useful in identification and strongly influence utilization of the species. Luster, odor, and taste are not of great use in identifying the hardwoods that are the subject of this text; exceptions might be the distinctive odor of freshly sawn red oak species, and the lustrous appearance of the ashes.

PITH

The pith of woody plants is the small central core of primary parenchymatous tissue differentiated from apical meristem tissue at the stem's growing tip and extending the length of the stem (fig. 5-3). The pith of woody plants is variable in appearance, color, size and shape; occasionally it may be of value in identification. For example, pith in transverse section appears **stellate** (star-shaped) in the oaks, sweetgum and hickory and **terete** (rounded) in the other species described in this chapter. Additionally, pith may be homogeneous, **chambered**, or **diaphragmed.** Homogeneous pith consists of solid, continuous material; diaphragmed pith is continuous, but has discs of transversely elongated cells at

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[1] See acknowledgements on the front page of this chapter.

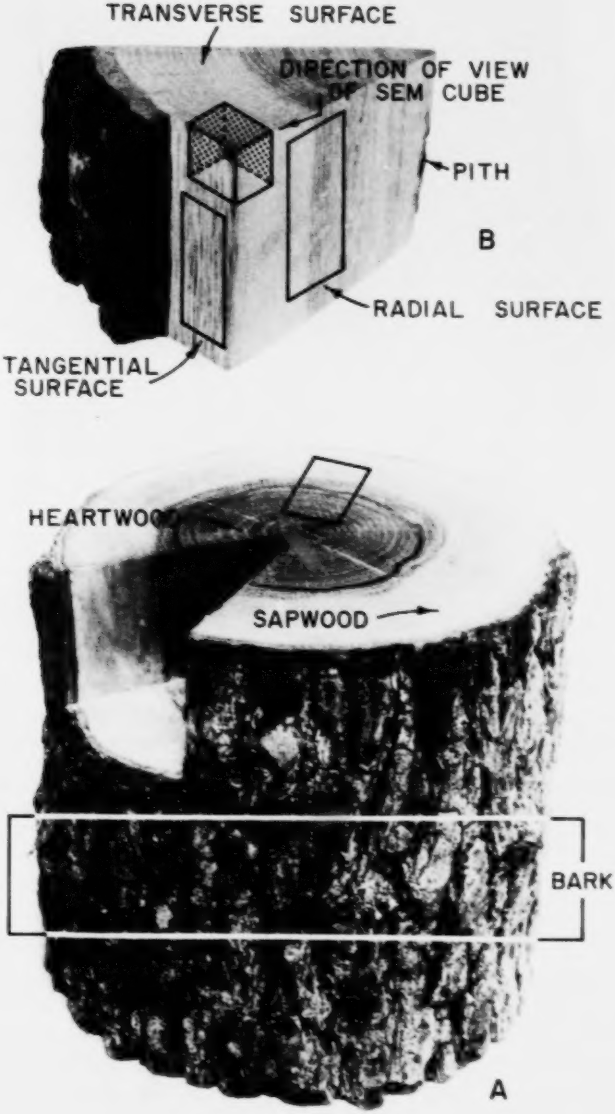

TRANSVERSE SURFACE
DIRECTION OF VIEW OF SEM CUBE
PITH
B
RADIAL SURFACE
TANGENTIAL SURFACE
HEARTWOOD
SAPWOOD
BARK
A

Figure 5-1.—Oak stem cut to expose study surfaces. (A) Portion of stem showing bark, sapwood, heartwood, and transverse study surfaces. (B) Section removed to show other study surfaces. For color photographs of bark see figures 13-1 through 13-6. (Photos from McMillin and Manwiller (1980).)

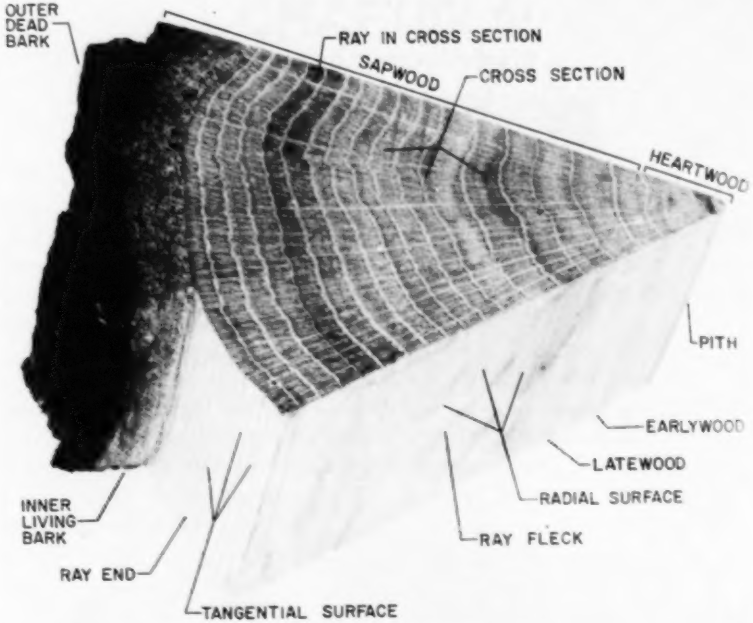

OUTER
DEAD
BARK
RAY IN CROSS SECTION
SAPWOOD
CROSS SECTION
HEARTWOOD
PITH
EARLYWOOD
LATEWOOD
RADIAL SURFACE
RAY FLECK
INNER
LIVING
BARK
RAY END
TANGENTIAL SURFACE

Figure 5-2.—Oak section similar to that in figure 5-1B, cut to illustrate study surfaces and features generally visible to the eye.

intervals giving the appearance of cross bars when the pith is exposed; and chambered pith is divided into empty horizontal chambers by cross partitions. The hardwoods of interest here were categorized by Harlow et al. (1979) as follows:

Pith terete in section			Pith stellate in section
Homogeneous	Chambered	Diaphragmed	Homogeneous
Ashes Elms Maples Magnolias	Hackberry	Black tupelo Yellow poplar	Oaks Sweetgum Hickory (somewhat)

Magnolia sp. pith may be inconspicuously diaphragmed and hackberry is finely chambered only at the nodes.

The pith is the focal point of radial checks ususally seen in the ends of dry hardwood logs and caused by tangential shrinkage during drying (fig. 5-3). Hardwood stems ripped longitudinally through the pith will, on drying, frequently develop a prominent longitudinal check coincident with the pith (fig. 5-3, bottom). Tangential shrinkage and associated pith-focused radial checks are major factors influencing the design, manufacture, drying, use, and appearance of solid hardwood products. The presence of pith in hardwood lumber is a grading defect in the better grades. Chapter 8 provides data on shrinkage and chapter 20 describes drying techniques to minimize degrade from checks.

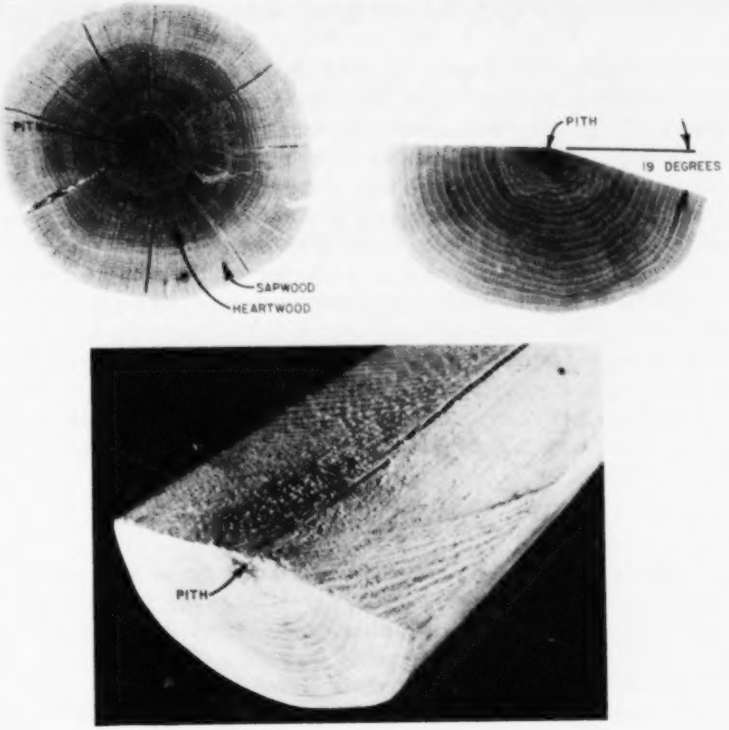


Figure 5-3.—Pith in 6-inch hardwoods. (Top left) Radial checks in dry cross section from chestnut oak. Also visible are sapwood (11-14 rings) and heartwood (36-39 rings); heartwood percentage is approximately 45 percent. (Top right) Stem of chestnut oak, ripped longitudinally through the pith when green, displays 19 degrees of tangential shrinkage when dried to 9 percent moisture content. (Bottom) Check coincident with pith in dry half-log of chestnut oak.

BARK AND WOOD

As described in chapter 4, wood (xylem) is formed to the inside and bark (phloem) to the outside of the **cambial layer.** Bark comprises about 15 percent of the dry weight of the aboveground biomass of entire hardwood trees 6 inches in diameter growing on pine sites; wood makes up about 82 percent and foliage the balance. In limb-free stems of such trees, roughly 85 percent of the dry weight is wood and 15 percent is bark. More detailed data on components of tree biomass are given in sections 16-1 and 27-3. The anatomy of bark and data on bark thickness and volume are described in chapter 13. For photos of bark of 6-inch hardwoods that are the subject of this text see figures 3-33 through 3-58 (black and white) and 13-1 through 13-6 (color).

PLANES OF WOOD FOR ANATOMICAL AND DESCRIPTIVE STUDY

The three-dimensional structure of wood can be conveniently described in terms of three planes (figs. 5-1 and 5-2). The cross section or **transverse section** is exposed when wood is cut at right angles to the grain or longitudinal axis. It is the surface exposed on the end of a log or board. The **tangential surface** is exposed when the bark is peeled from a tree or when veneer is rotary-cut; an element of this surface is perpendicular to the rays. A **radial surface** or section is formed by producing a plane parallel to the longitudinal axis of the tree and passing through the pith. A sawyer producing vertical grain flooring would expose this surface, as would a slicer veneer operator making quarter-cut veneer. The surface of flat- or plain-sawn lumber is essentially tangent to the growth rings and at right angles to the rays while quarter-sawn lumber is parallel to the rays and at right angles to the growth rings.

These specified planes are useful because they are easily produced using growth rings, rays, and grain and tissue arrangements for refernce.

GROWTH RINGS

A **growth ring** in pine-site hardwoods is the end surface or cross section of the yearly increment of wood produced by the cambium (fig. 5-2). Growth rings may be divided into two zones, earlywood and latewood. **Earlywood** is produced during the first part of the growing season, usually while apical growth is most active. **Latewood** is produced during the latter part of the season. In many woods, there is noticeable difference between these two zones due to changes in cell size, cell wall thickness and cell arrangement. In other woods, arbitrary definitions must be made. Physiological controls over width of growth rings and latewood formation are complex and, for hardwoods, not well understood. Information correlating climate with width of annual rings may be found in the following references: Fritts (1959, 1962), Harper (1961), Estes (1970), and Johnson and Risser (1973).

Growth rings in hardwoods growing on southern pine sites may be distinct or indistinct depending upon the patterns formed by vessels and parenchyma and on the abruptness of transition between the thicker-walled or more tabular cells (fibers) of the outer latewood and the thinner-walled, more circular cells of the succeeding year's growth of earlywood (table 5-1 and figs. 5-4 through 5-15 and figs. 5-22 through 5-45).

Total width of **annual ring,** i.e., the earlywood plus the latewood growth for one year, may range from less than 1/32-inch to more than 1/2-inch. Thirteen annual rings per inch of tree radius—while not an average for all hardwood species—is common on pine sites (table 3-1). Using tracheid diameters (table 5-7) of true hickory as an example, and assuming 40 percent of the .08-inch-wide annual ring to be latewood, then one radial file of cells in the annual ring would contain 90-120 earlywood and latewood fibers, 0-2 earlywood vessels, 0-3 latewood vessels, and 12-18 parenchyma cells. Faster growing yellow-poplar, 30 years of age with ring widths of 0.1 to 0.25 inch, were observed to contain

100-200 fibers plus 12-28 vessels and a few marginal parenchyma cells in each radial file across an annual ring. Foulger et al. (1975) found that annual ring widths in yellow-poplar were minimum near ground level and maximum at an upper level five to eight internodes below the intersection of each annual growth sheath with the pith. Similarly, in red maple, McDougall (1963) found that maximum width in a growth sheath occurred within the top five internodes below its intersection with the pith.

TABLE 5-1.—*Characteristics of growth rings of hardwoods grown on southern pine sites*

Species	Growth Rings	Transition from earlywood to latewood
Ashes	Distinct	Abrupt
Elms	Distinct	Abrupt
Hackberry	Distinct	Abrupt
Hickories, true	Distinct	Abrupt
Maple, red	Distinct	Gradual or not evident
Oaks, red	Distinct	Abrupt
Oaks, white	Distinct	Abrupt
Sweetbay	Distinct	Gradual or not evident
Sweetgum	Distinct to indistinct	Gradual or not evident
Tupelo, black	Indistinct	Gradual or not evident
Yellow-poplar	Distinct	Gradual or not evident

Duration of annual radial growth varies substantially among species, as discussed in chapter 4. Annual growth also varies greatly within species; for example, a 2-year study of seasonal changes in diameter revealed that dominant and codominant black oaks grew faster and for a longer period during the growing season than did overtopped trees (Buchanan et al. 1962). Trimble (1969) also found stem diameter positively correlated with diameter growth in uniform stands, i.e., faster growing trees were larger. In diversified stands of hardwoods, however, diameter growth was best correlated with "crown class", calculated as the product of crown length and diameter. Shortle et al. (1977) found that rate of growth in sprout red maple was inversely proportioned to resistance to pulsed electric current in the cambial zone; i.e., rapidly growing trees have a wide cambial zone with low electrical resistance.

For most uses, concentricity of annual rings is a desirable quality because the pith of concentric stems is in a predictable position and can be eliminated during processing if desired. Most hardwood trees from pine sites, however, are not consistently concentric. In 20 straight-boled post oaks, only 11.8 percent of the tested cross sections were concentric and 35 percent of the trees had no concentric sections at any measured height; between-tree variance is eccentricity was greater than within-tree variance (Salem 1961).

In a study of six 12- to 20-inch yellow-poplar cut in Durham County, North Carolina, Taylor (1965) found that eccentricity of bole varied at successive heights in the trees, with no particular pattern evident. The pith was virtually never in the geometric center of the bole, but was within 1-1/2 inches of it.

Distinguishing growth rings is particularly difficult in diffuse-porous woods. Temporary staining with phloroglucinol solution, which stains the lignin red, is one technique (Patterson 1959). Others, perhaps more useful, include radiography with X-rays (Renton et al. 1974; Parker et al. 1976) and gamma densitometry, a somewhat similar technique.

VESSEL (PORE) SIZE AND ARRANGEMENT ACROSS THE GROWTH RING

Hardwood fibers have a less orderly arrangement than softwood fibers in that they are interspersed with shorter, thinner-walled parenchyma and with shorter, but much larger-diameter **vessel elements** (called pores in cross section). **Vessels** consist of open-ended tubular vessel elements arranged one above the other in a relatively continuous structure.

Each species of hardwoods usually is characterized by distinct and different arrangements or patterns of vessels within an annual ring. For convenience, however, all of the hardwood species can be classified into three broad patterns visible with the naked eye or with a low-power hand lens.

In **ring-porous woods,** vessels formed at the beginning of the growing season (earlywood) are much larger than those farther out in the ring (fig. 5-4, bottom). **Diffuse-porous** woods have vessels which exhibit little or no variation in size or distribution throughout the annual ring (fig. 5-7, top). **Semi-ring-porous** woods (sometimes termed **semi-diffuse-porous**) have vessel patterns intermediate between ring-porous and diffuse-porous woods. None of the woods in this chapter are truly semi-ring-porous, although the red oaks occasionally approach this arrangement (figs. 5-9, bottom; 5-11, top and bottom. These examples also are shown at higher magnification in figs. 5-23 through 5-45).

LATEWOOD VESSEL ARRANGEMENT

Vessels in the latewood of ring-porous woods and, to some extent, in diffuse-porous woods, may be distributed in recognizable patterns or groupings. Among these are the **dendritic** arrangement of oak latewood vessels (figs. 5-7 bottom through 5-13 top, and fig. 5-46), the uniform abundant and **solitary** distribution of sweetgum vessels or pores (figs. 5-14 top and 5-47 left), the **ulmiform** pattern of the elm and hackberry vessels (figs. 5-5, 5-6 top, and 5-48), and the rather sparse **radial multiples** of the vessels in the hickories, ashes (figs. 5-4, 5-6 bottom, and 5-49), sweetbay, and red maple (fig. 5-50).

Of the hardwoods growing among southern pines primarily considered in this text, none is classified as semi-ring-porous; they are ring- or diffuse-porous as follows:

Ring-porous

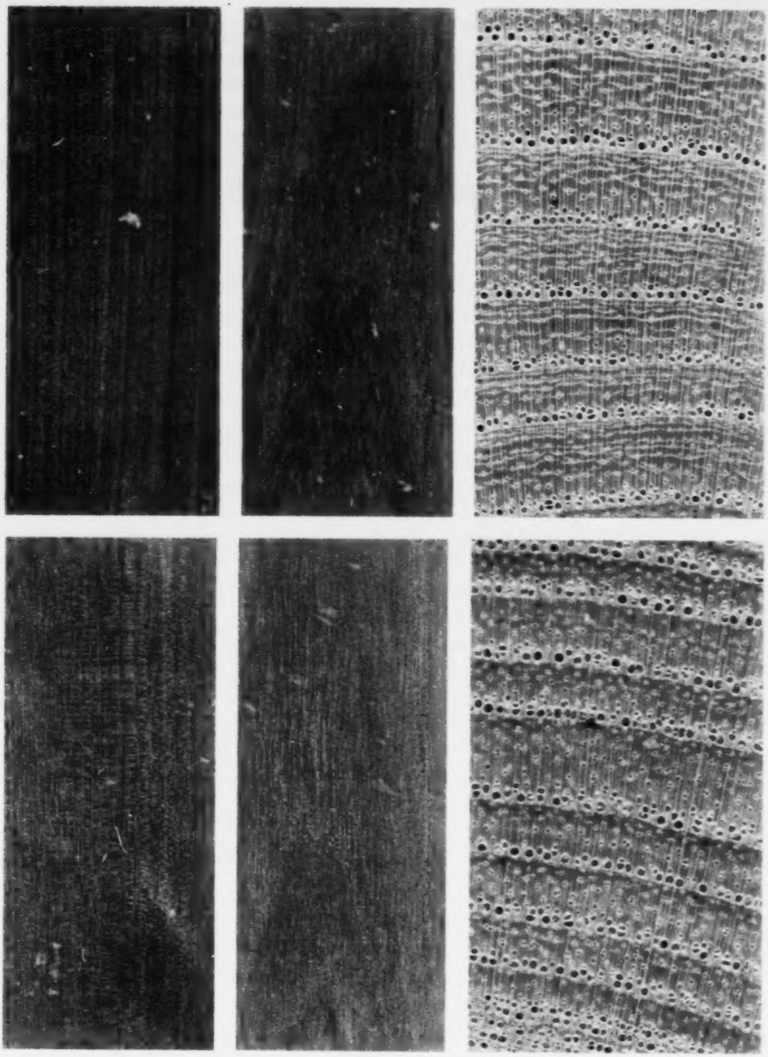
Ash, green (fig. 5-4 top)
Ash, white (fig. 5-4, bottom)
Elm, American (fig. 5-5, top)
Elm, winged (fig. 5-5, bottom)
Hackberry (fig. 5-6, top)
Hickory, true (fig. 5-6, bottom)
Oak, black (fig. 5-7, bottom)
Oak, blackjack (fig. 5-8, top)
Oak, cherrybark (fig. 5-8, bottom)
Oak, chestnut (fig. 5-9, top)
Oak, laurel (fig. 5-9, bottom)
Oak, northern red (fig. 5-10, top)
Oak, post (fig. 5-10, bottom)
Oak, scarlet (fig. 5-11, top)
Oak, Shumard (fig. 5-11, bottom)
Oak, southern red (fig. 5-12, top)
Oak, water (fig. 5-13, bottom)
Oak, white (fig. 5-13, top)

Diffuse-porous

Maple, red (fig. 5-7, top)
Sweetbay (fig. 5-13, bottom)
Sweetgum (fig. 5-14, top)
Tupelo, black (fig. 5-14, bottom)
Yellow-poplar (fig. 5-15)

Vessel size, wall thickness, and distribution are aids to identification. Viewed in cross section with a hand lens, orifices of the thick-walled, rounded, sparsely distributed latewood vessels of the red oaks are plainly visible whereas those of the abundant thin-walled, angular, latewood vessels of white oaks (chestnut, post, white) are scarcely discernible (fig. 5-46).

Distribution of vessels in some species is strongly influenced by width of growth rings (see sec. 5-10 and fig. 5-106).

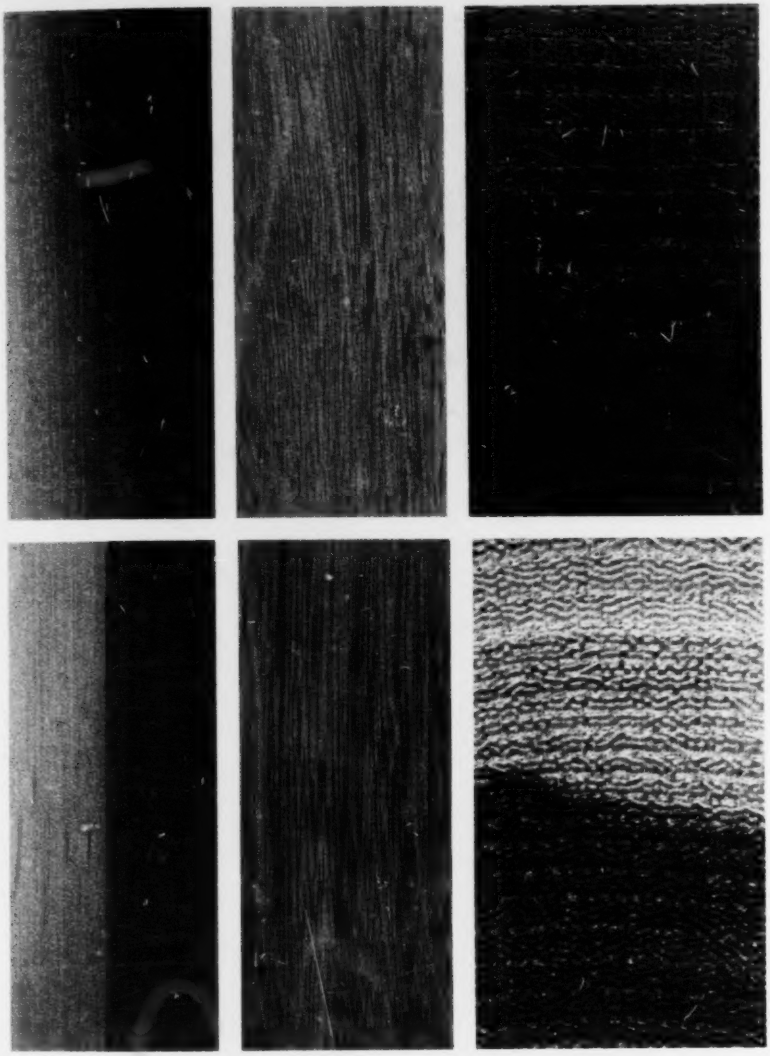


Radial
Mag. x1

Tangential
Mag. x1

Transverse
Mag. x5

Figure 5-4.—(Top) Ash, green. (Bottom) Ash, white. See also figures 5-23 and 5-24. (Photos from McMillin and Manwiller 1980.)

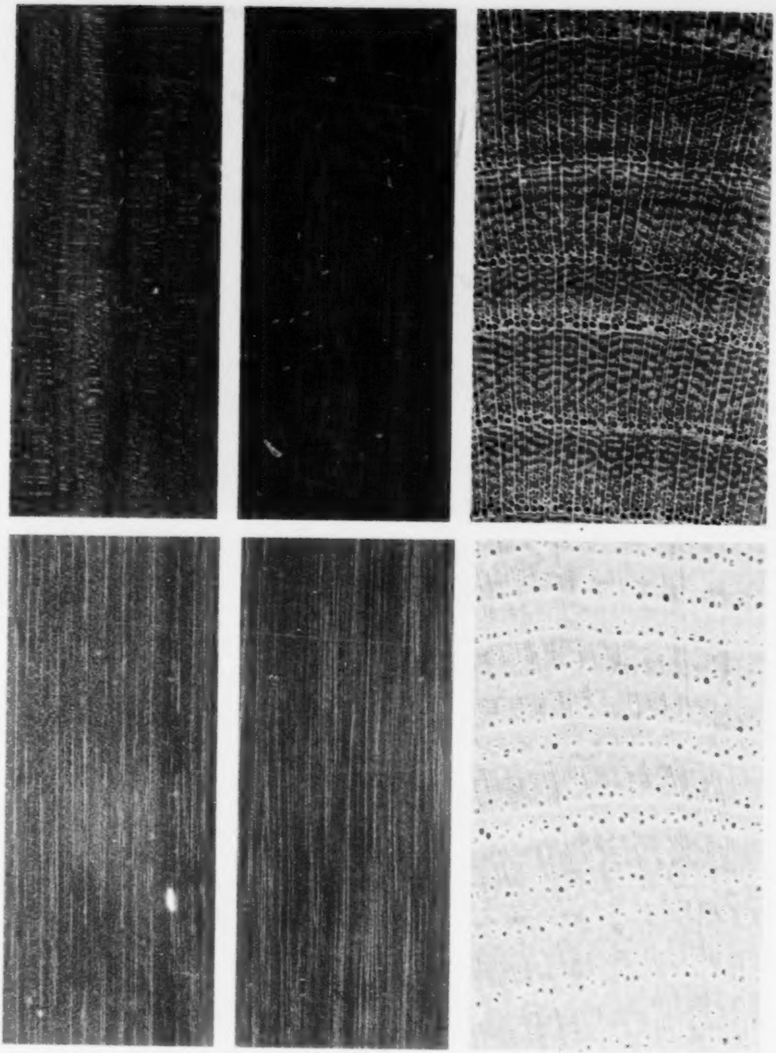


Radial
Mag. x1

Tangential
Mag. x1

Transverse
Mag. x5

Figure 5-5.—(Top) Elm, American. (Bottom) Elm, winged. See also figures 5-25 and 5-26. (Photos from McMillin and Manwiller 1980.)

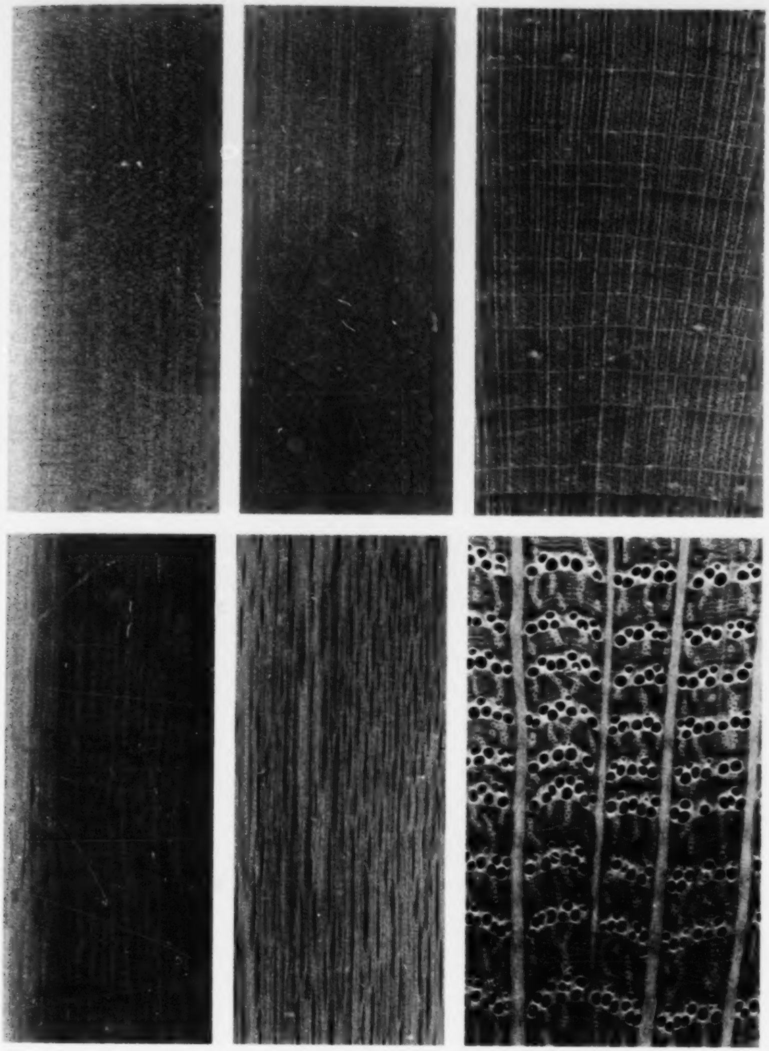


Radial Mag. x1

Tangential Mag. x1

Transverse Mag. x5

Figure 5-6.—(Top) Hackberry. (Bottom) Hickory, true. See also figures 5-27 and 5-28. (Photos from McMillin and Manwiller 1980.)

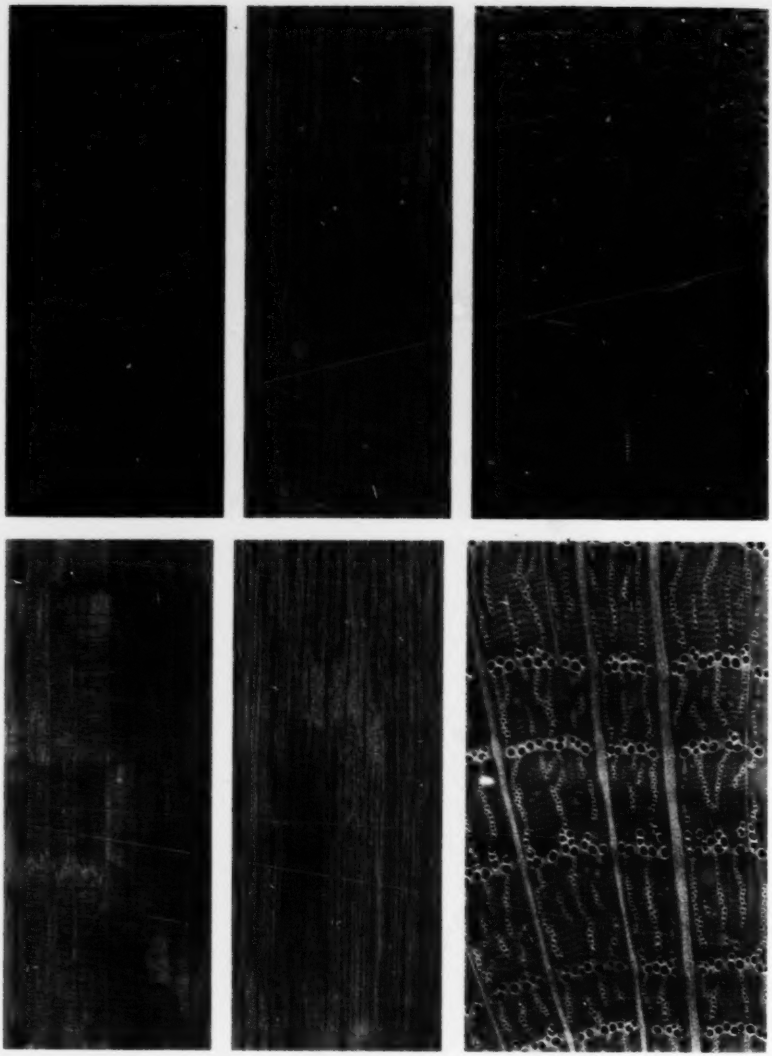


Radial
Mag. x1

Tangential
Mag. x1

Transverse
Mag. x5

Figure 5-7.—(Top) Maple, red. (Bottom) Oak, black. See also figures 5-29 and 5-30. (Photos from McMillin and Manwiller 1980).

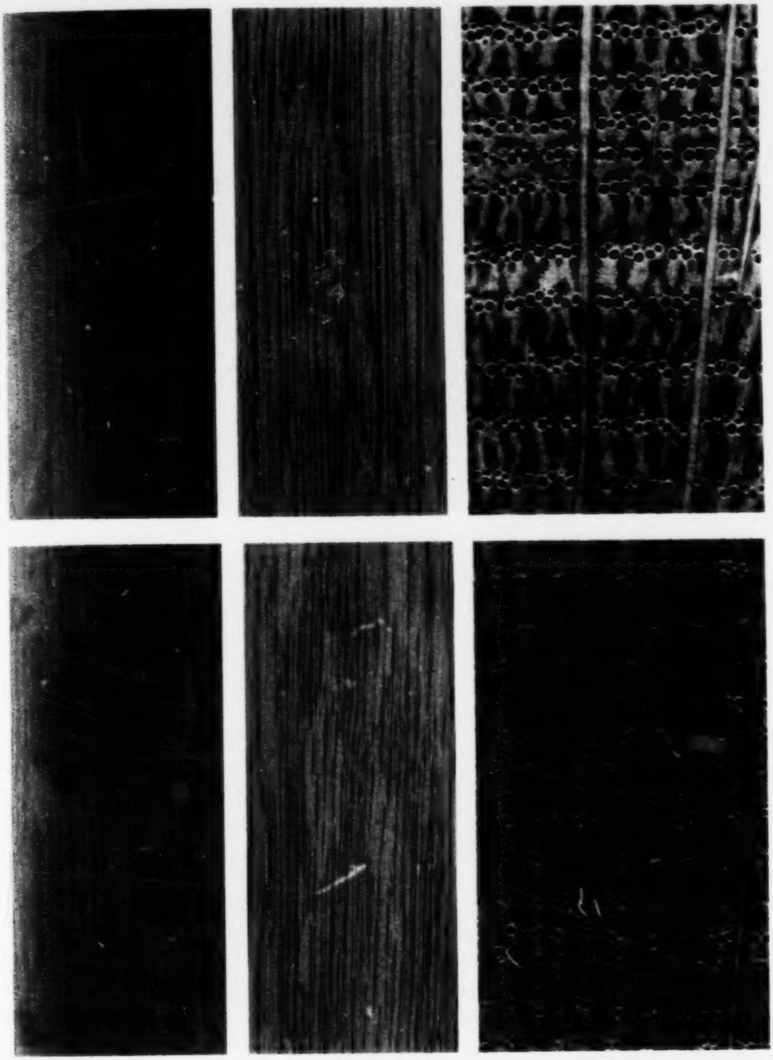


Radial
Mag. x1

Tangential
Mag. x1

Transverse
Mag. x5

Figure 5-8.—(Top) Oak, blackjack. (Bottom) Oak, cherrybark. See also figures 5-31 and 5-32. (Photos from McMillin and Manwiller 1980.)

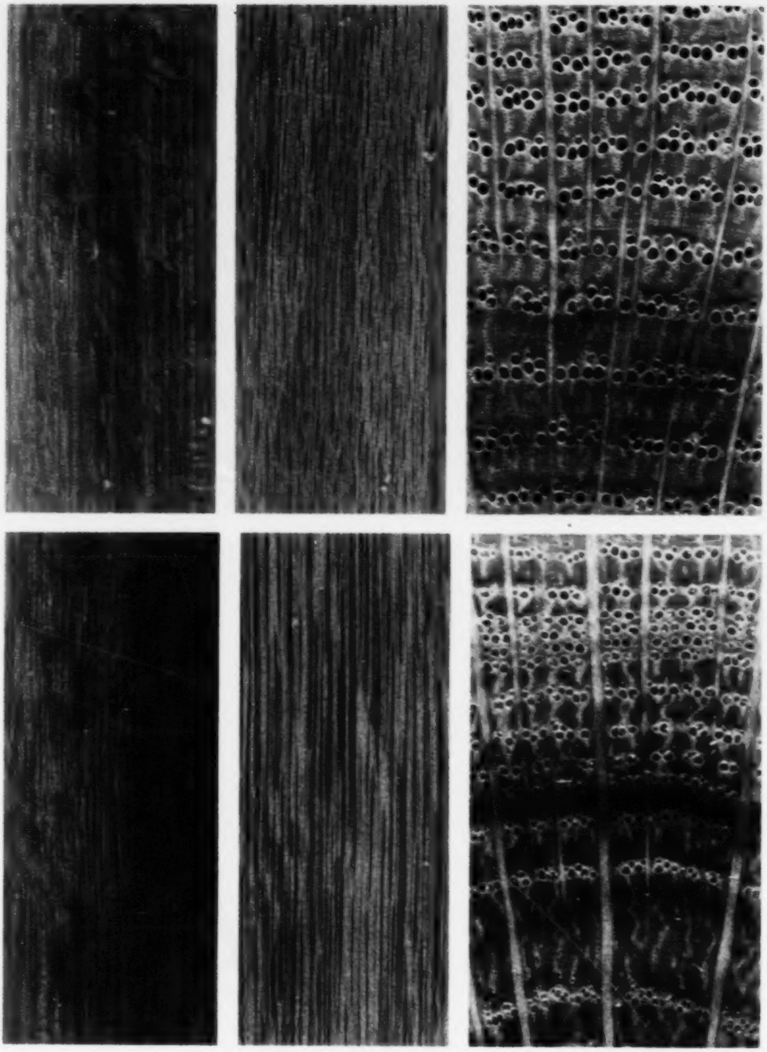


Radial
Mag. x1

Tangential
Mag. x1

Transverse
Mag. x5

Figure 5-9.—(Top) Oak, chestnut. (Bottom) Oak, laurel. See also figures 5-33 and 5-34. (Photos from McMillin and Manwiller 1980).

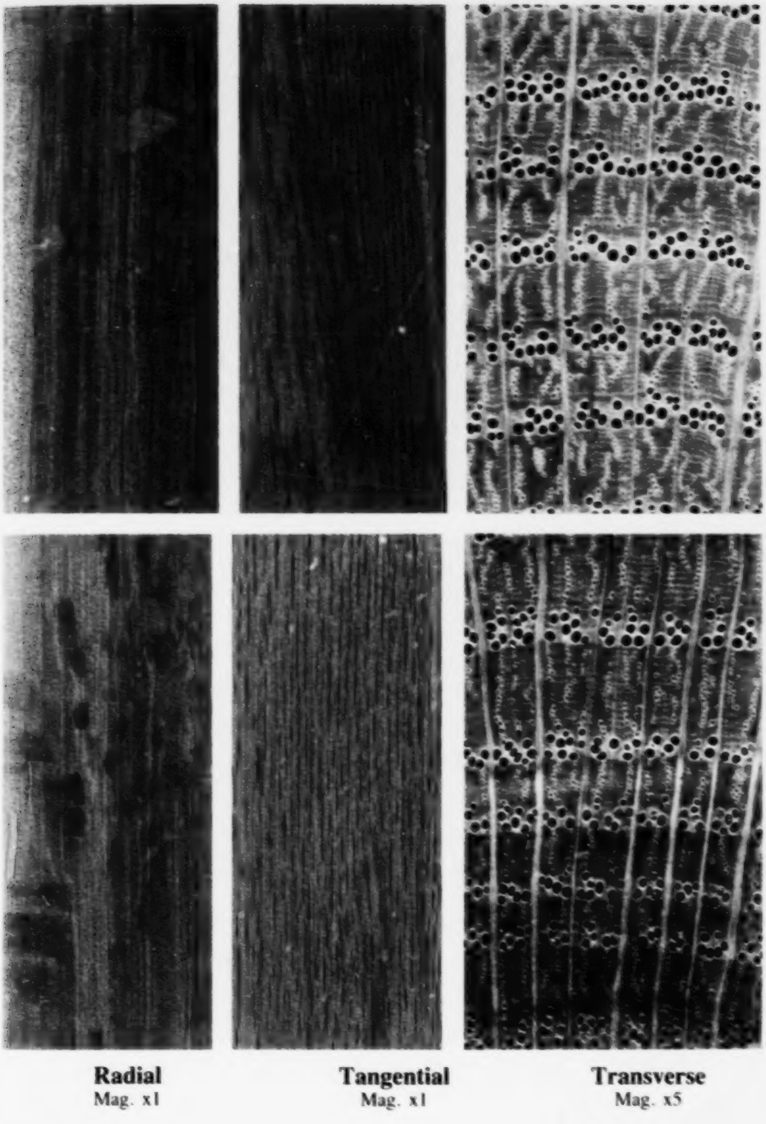


Radial
Mag. x1

Tangential
Mag. x1

Transverse
Mag. x5

Figure 5-10.—(Top) Oak, northern red. (Bottom) Oak, post. See also figures 5-35 and 5-36. (Photos from McMillin and Manwiller 1980.)

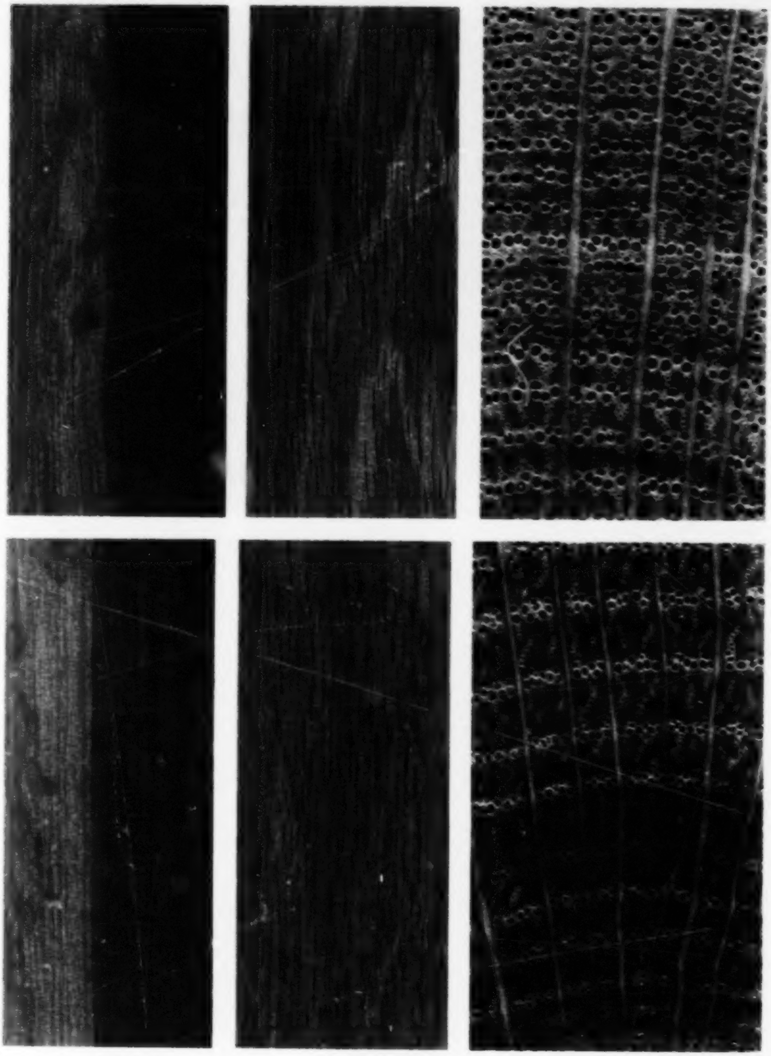


Radial
Mag. x1

Tangential
Mag. x1

Transverse
Mag. x5

Figure 5-11.—(Top) Oak, scarlet. (Bottom) Oak, Shumard. See also figures 5-37 and 5-38. (Photos from McMillin and Manwiller 1980.)

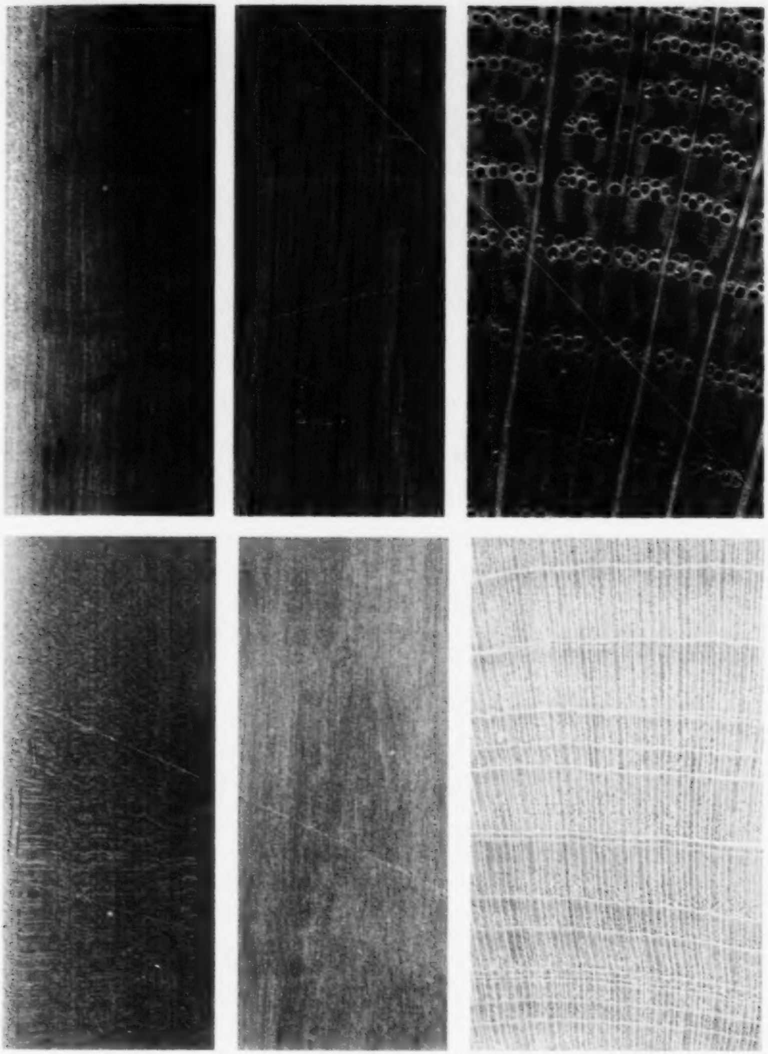


Radial
Mag. x1

Tangential
Mag. x1

Transverse
Mag. x5

Figure 5-12.—(Top) Oak, southern red. (Bottom) Oak, water. See also figures 5-39 and 5-40. (Photos from McMillin and Manwiller 1980.)

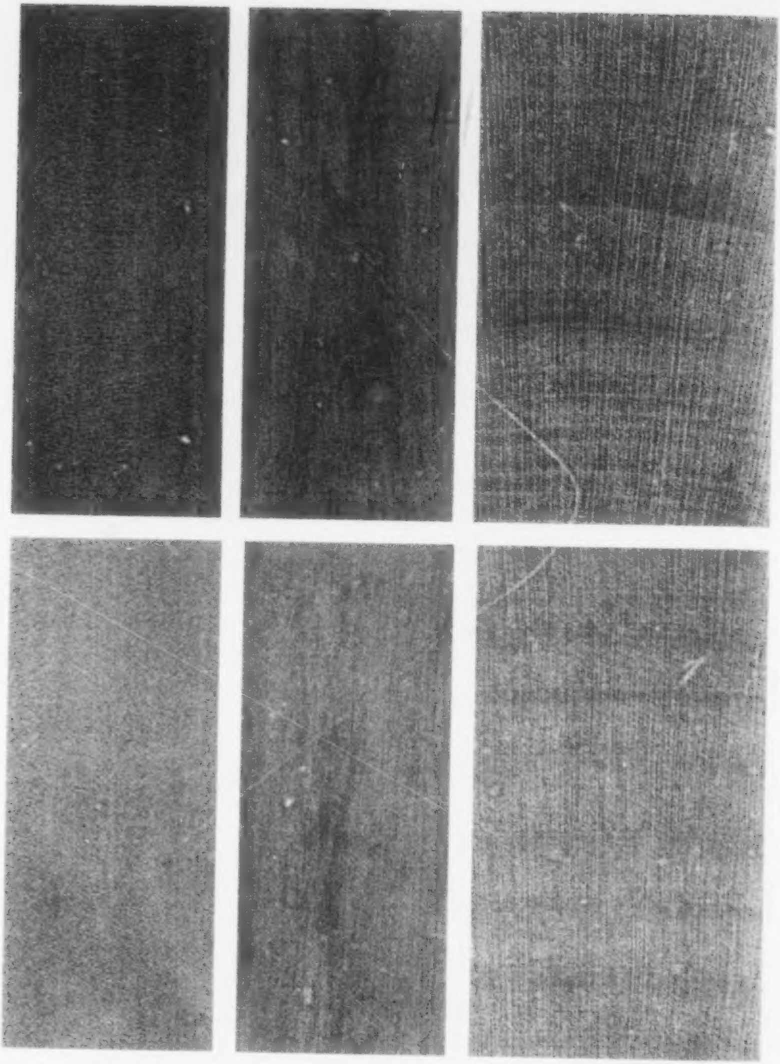


Radial
Mag. x1

Tangential
Mag. x1

Transverse
Mag. x5

Figure 5-13.—(Top) Oak, white. (Bottom) Sweetbay. See also figures 5-41 and 5-42. (Photos from McMillin and Manwiller 1980.)

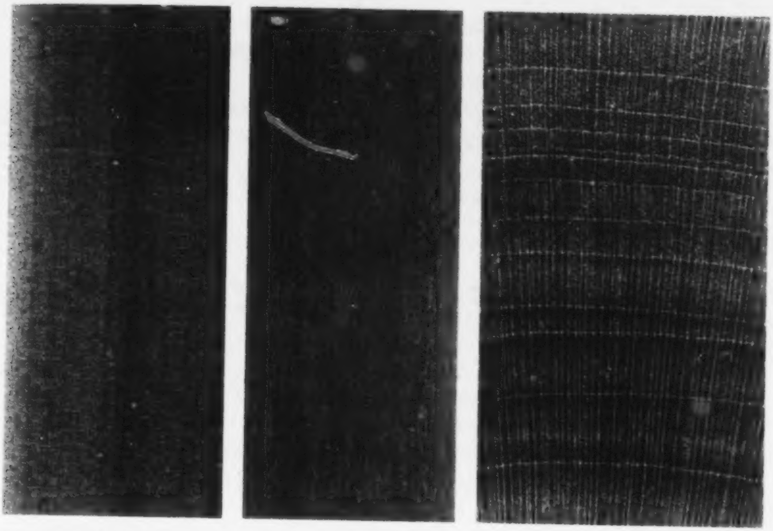


Radial
Mag. x1

Tangential
Mag. x1

Transverse
Mag. x5

Figure 5-14.—(Top) Sweetgum. (Bottom) Tupelo, black. See also figures 5-43 and 5-44. (Photos from McMillin and Manwiller 1980.)



Radial
Mag. x1

Tangential
Mag. x1

Transverse
Mag. x5

Figure 5-15.—Yellow-poplar. See also figure 5-45. (Photos from McMillin and Manwiller 1980.)

PARENCHYMA PATTERNS

Wood **parenchyma cells,** which store and conduct food materials, usually are numerous in hardwoods; in sapwood these are living cells but they lose their living protoplasm when sapwood is transformed to heartwood. There are two types of such cells in hardwoods: **ray parenchyma,** which constitute the ray tissue and which are radially (transversely) oriented to the stem axis, and **axial (longitudinal) parenchyma,** which extend longitudinally in the form of strands comprised of individual cells. In transverse section, longitudinal parenchyma cells may form patterns visible by naked eye or hand lens, distinctive to species or species groups and useful in distinguishing species.

Jane (1970) described three major patterns or arrangements of longitudinal parenchyma as viewed in transverse section (fig. 5-51): **apotracheal,** that not associated with vessels and vascular tracheids (figs. 5-6 bottom, 5-22, 5-28, and 5-49 left); **paratracheal,** that associated with vessels and vascular tracheids (figs. 5-4, 5-9 top, 5-22, and 5-49 right); and **boundary (marginal) parenchyma** forming a zone at the end, i.e., **terminal,** or at the beginning, i.e., **initial,** of a growth ring (figs. 5-15, 5-45, 5-50 right). Some authorities use the term

marginal in preference to boundary parenchyma. Additionally, **epithelial parenchyma** encircle longitudinal gum canals sporadically found in wounded sweetgum. Also, an abundance of axial parenchyma may be found in abnormal tissue formed following injury (Smith 1980).

Figure 5-51, summarizing parenchyma arrangements, studied in conjunction with figures 5-4 through 5-15 and 5-23 through 5-45, should be helpful in species identification.

RAY PATTERNS

Wood rays, ribbon-like aggregations of cells extending in the radial direction, i.e., from the bark toward the center of the tree, form patterns often readily seen with the naked eye on transverse and radial surfaces and, occasionally, on tangential surfaces. In transverse section, rays appear as lines of various widths, running radially toward the pith. On radial surfaces they appear as flecks or ribbons; and on tangential surfaces they range from short (not visible to eye) vertical dashes, up to readily visible 1-inch-long staggered lines (in the oaks) running parallel to the grain (figs. 5-4 through 5-15).

Section 5-5 describes the minute anatomy of rays and provides a diagram (fig. 5-56) useful for identification with a microscope. The unassisted eye, however, can easily distinguish oaks by their broad ray flecks visible in radial section, and the tall vertical lines seen in tangential section (figs. 5-1; 5-7 bottom, through 5-13 top).

Spacing and coloration of rays, as well as size, also are useful in distinguishing species. The closely-spaced rays of black tupelo and sweetgum occupy a sizeable part of the cross section (figs. 5-14 and 5-47). Hackberry (figs. 5-6 and 5-48 right), sweetbay, and yellow-poplar (figs. 5-13 bottom and 5-15) cross sections display distinctly visible rays with more normal spacing.

SAPWOOD AND HEARTWOOD

The sapwood of the trunk and branches of many—but not all—uninjured trees changes, usually abruptly, in appearance and function after a certain age. This interior core is **heartwood,** of which one definition is: the inner zone of wood which, in the growing tree, has ceased to contain living cells and in which the reserve materials (e.g., starch) have been removed or converted into heartwood substances. It is generally darker in color than sapwood, though not always clearly differentiated (International Association of Wood Anatomists, Committee on Nomenclature 1964).

Hardwoods on pine sites—and those that will grow in the foreseeable future—will be utilized in diameters generally less than 15 inches, with most of the volume from trees of 12-inch dbh or smaller. In such small logs, e.g., 6 inches in diameter, coloration in heartwood is readily distinguished from that of sapwood in more than half of the species, as follows (fig. 5-16):

Prominent heartwood coloration

Elm, winged
Elm, American
Oak, black
Oak, blackjack
Oak, cherrybark
Oak, chestnut
Oak, laurel
Oak, northern red
Oak, post
Oak, scarlet
Oal, Shumard
Oak, southern red
Oak, water
Oak, white
Yellow-poplar

Heartwood color not markedly different from sapwood

Ash, green
Ash, white
Black tupelo
Hickory, sp.
Red maple
Hackberry
Sweetbay
Sweetgum

Some authorities have found that the species in the right-hand tabulation have no normal heartwood, only injury-altered wood (personal correspondence with A.L. Shigo, March 1982).

In larger logs, i.e., of size suitable for veneer peeling, color differences may be more apparent, as described in table 5-2.

Because heartwood content influences utilization of hardwoods, it is useful to know something about width of sapwood. Some woods such as black tupelo are slow to form heartwood, while others may begin heartwood formation within a few growth rings of the cambium (table 5-2).

TABLE 5-2.—*Width of sapwood and color of heartwood and sapwood of some southern hardwoods* (Lutz 1972)

Species	Sapwood color	Heartwood color	Approximate width of veneer-log sapwood
			Inches
Ash, green[1]	white to pale yellow	very light brown	3-8
Ash, white[1]	white to pale yellow	very light brown	3-6
Elm, American	gray-white	light gray-brown often tinged with red	1.5-3
Elm, winged	gray-white	light gray-brown often tinged with red	1.5-2
Hackberry	pale yellow to greenish-gray	same as sapwood but darker	3-8
Hickory, true	white to light pinkish brown	reddish-brown with darker streaks	1.5-3

See following page for footnote.

TABLE 5-2.—*Width of sapwood and color of heartwood and sapwood of some southern hardwoods* (Lutz 1972)—continued.

Species	Sapwood color	Heartwood color	Approximate width of veneer-log sapwood
			Inches
Maple, red[1]	white, may be tinged red-brown	light red-brown	3-5
RED OAKS			
Oak, black	white	gray-brown with pinkish tinge	1-3
Oak, blackjack	—	—	—
Oak, cherrybark	white	gray-brown with pinkish tinge	1.5-2.5
Oak, laurel	white	gray-brown with pinkish tinge	1.5-2.5
Oak, northern red	white	gray-brown with pinkish tinge	1.5-2.5
Oak, scarlet	white	gray-brown with pinkish tinge	1.5-2
Oak, Shumard	white	gray-brown with pinkish tinge	1.5-2.5
Oak, southern red	white	gray-brown with pinkish tinge	1.5-2.5
Oak, water	white	gray-brown with pinkish tinge	2-3
WHITE OAKS			
Oak, chestnut	white	light or pale gray-brown	1-2
Oak, post	white	light or pale gray-brown	1-2
Oak, white (*Quercus alba*)	white	light or pale gray-brown	1.5-2
Sweetbay	white	light yellow-brown, occas. dark green or purple streaks	1.5-5
Sweetgum	pinkish-white	reddish-brown, often with irreg. dark streaks	5-8
Tupelo, black	white	pale brown-gray	2-4
Yellow-poplar	white	light yellow-brown, occas. dark green or purple streaks	1.5-5

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[1] According to Shigo (1975), maples and ashes do not have true heartwood, the discolored wood that frequently is present in the central portion is injury-altered wood.

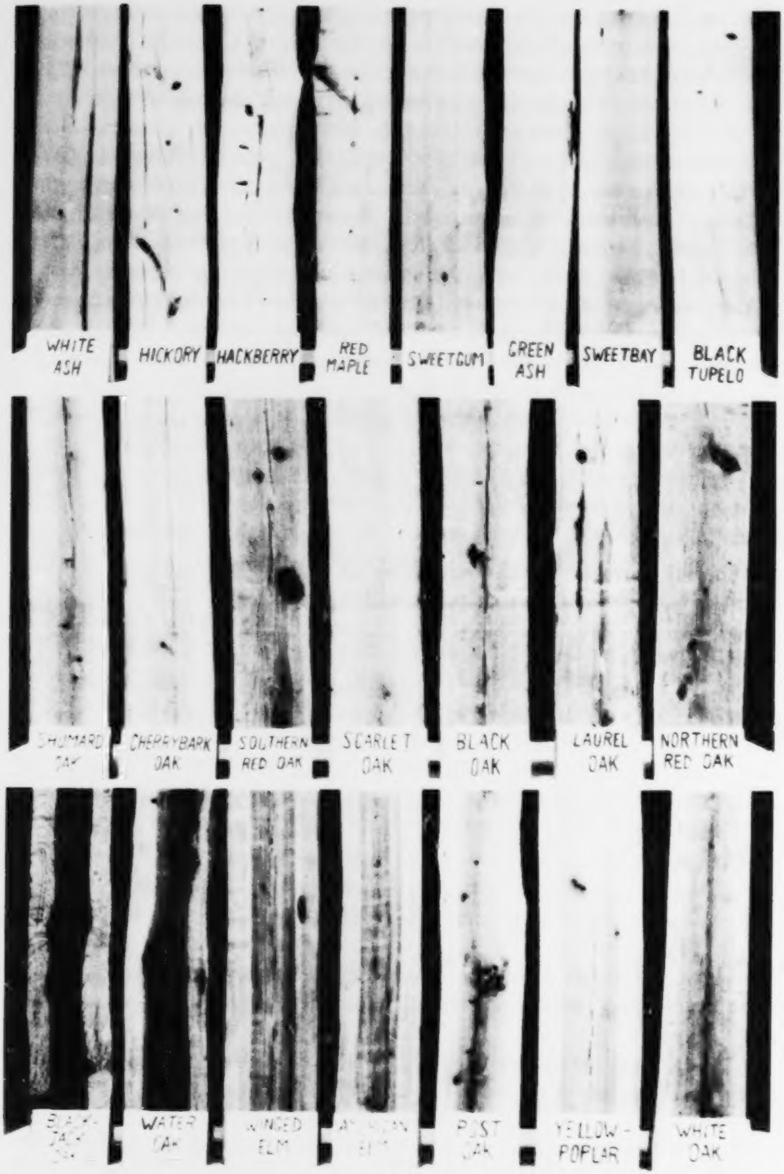
WHITE ASH
HICKORY
HACKBERRY
RED MAPLE
SWEETGUM
GREEN ASH
SWEETBAY
BLACK TUPELO
SHUMARD OAK
CHERRYBARK OAK
SOUTHERN RED OAK
SCARLET OAK
BLACK OAK
LAUREL OAK
NORTHERN RED OAK
BLACK-JACK OAK
WATER OAK
WINGED ELM
AMERICAN ELM
POST OAK
YELLOW-POPLAR
WHITE OAK

Figure 5-16.—Heartwood and sapwood in mid to lower stem sections of trees 6 inches in dbh (about 40 yars old) cut from southern pine sites. Sections shown average 4¾ inches in diameter. Species with little color difference between heartwood and sapwood are shown at top; those with most difference at bottom. Chestnut oak is missing from the photograph but probably would be placed between post oak and yellow-poplar.

Heartwood is age-altered wood, and it is different from the discolored wood resulting from injury as described in chapter 11 and Shigo (1975). Normal heartwood differs from sapwood in characteristics other than color. Most important are differences in chemical constituents (chapter 6), permeability (compare fig. 5-39 with 5-41, and see chapter 8), moisture content (chapter 8), and resistivity to insect and fungal attack (chapter 11). In general, heartwood lumber of hardwoods from southern pine sites is darker in color, is denser (due to extraneous deposits), has less ash content, is more acidic, is less permeable, has higher moisture content, and is more resistant to insect and fungal attack than is sapwood from the same species. Illustrative of density, ash content and pH differences are data on southern red oak heartwood and sapwood from Sachs et al. (1966), as follows (average of three logs from Kentucky and one from Virginia):

Tissue type	Specific gravity (O.D. vol. and wt.)	Ash content	pH
		Percent	*Range*
Sapwood (no stain)........	0.708	0.731	5.1-5.6
Heartwood (no stain)......	.773	.319	3.4-3.8
Heartwood (discolored)....	.827	.460	3.6-3.8

In white oak, ash content was observed highest in discolored sapwood, intermediate in sapwood without stain, and lowest in heartwood; the pH of cold water extract was similar for sapwood and heartwood, and lowest for discolored sapwood (Wardell 1971).

There is a very large literature on heartwood, but readers are cautioned that confusion arises because many researchers have studied specimens cut from lumber, not living trees, and have not distinguished true heartwood from discolored sapwood or wetwood sapwood. To appreciate the complexity and variability of differences between heartwood and sapwood, an understanding of the formation of heartwood is useful.

Formation of heartwood.[2]—Like most temperate-zone trees, pine-site hardwoods develop central cones of heartwood within the sapwood of their stems and major branches. Heartwood consists mainly of nonliving cells and usually is richer in extractives.

Heartwood formation, once initiated, continues through the life of the tree, often maintaining a fairly constant width of sapwood, or number of sapwood rings for years.

The little available information indicates that the area of sapwood relative to heartwood is greater in the trunk than in branches of similar size, but the ratio can vary with species.

The transformation of sapwood to heartwood is initiated internally, not by external conditions. It is accompanied by necrosis of the parenchyma, which is alive in sapwood; some enzymatic activity may be found in the heartwood, however (Shain and MacKay 1973; Stutz 1959). Other major differences from sapwood in angiosperms can include formation of tyloses or gum when the pit apertures are less than 10 μm in diameter (Chattaway 1949). Although starch is absent from heartwood, small amounts of free sugar may be present (Hillis 1968). The nitrogen content is lower (Merrill and Cowling 1966), and the pH higher than in sapwood (Hillis 1968). Fatty materials that are stored in sapwood of some hardwoods, rather then starch, are changed in composition as heartwood forms (Hemingway and Hillis 1971; Mutton 1962). Most noticeable is the formation of nonstructural materials (extractives), in some southern hardwoods up to 10 percent of dry weight. These extractives incease density, coloration, and in some species, durability (Hillis 1962, 1968, 1971).

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[2] The text under this heading is condensed from Shigo and Hillis (1973).

The composition of secondary compounds in heartwood varies with family, genus, and species to an extent that permits identification of some species from their heartwood extractives (Hillis 1962); in others, however, within-species variation is considerable (Hillis 1966, 1968). Fraenkel (1959) suggested that extractives in heartwood (and in discolored wood) are possibly associated with the evolution of resistance to insect predators and decay micro-organisms.

Much of the published data supports the view that extractives are formed at the heartwood periphery from carbohydrates (Hillis 1971), although other views have been expressed (Stewart 1966). Hemingway and Hillis (1970) suggested that the factors controlling the amount and composition of heartwood extractives may be incorporated in the ray cells during the early stages of their development.

Colors in heartwood are due largely to extractives. The amount in heartwoods of similar age of some species is in part genetically controlled (Franklin et al. 1970), but a fast growth rate can reduce extractive formation (Hillis 1971), and even the soil type can affect the color (Nelson et al. 1969).

While the heartwood of conifers usually contains less moisture than sapwood, the heartwood of some hardwood species contains more moisture than the sapwood (Hillis 1968; Yazawa et al. 1965; Yazawa and Ishida 1965). The U.S. Department of Agriculture, Forest Service (1974) gives heartwood and sapwood moisture contents of some of the species discussed in this chapter as follows (ovendry-weight basis):

Species	Heartwood	Sapwood
	Percent	
Ash, green	—	58
Ash, white	46	44
Elm, American	95	92
Hackberry	61	65
Hickory, bitternut	80	54
Hickory, mockernut	70	52
Oak, northern red	80	69
Oak, southern red	83	75
Oak, white	64	78
Sweetgum, (redgum)	79	137
Tupelo, black	87	115
Yellow-poplar	83	106

The gas in the heartwood of some tree species contains, in addition to nitrogen, a large proportion of carbon dioxide and a small amount of oxygen (Dadswell and Hillis 1962; Jensen 1967; MacDougal et al. 1929).

Freshly cut cross sections of many tree species reveal a transition, intermediate, or white zone surrounding the heartwood, usually less than 1 cm wide, sometimes increasing with tree height and with season. The transition zone is paler in color than heartwood, but clearly distinguishable from the sapwood, the moisture content sometimes lower than that of the heartwood (Dadswell and Hillis 1962; Yazawa et al. 1965). It contains increased amounts of nicotinic acid amide, biotin, pyridoxine, and in some cases, protein nitrogen (Ziegler 1963, 1967).

Cytological studies of ring-porous hardwoods have shown increased vitality in the parenchymous cells (Hugentobler 1965), and increased respiration (Zelawski 1960) at the heartwood periphery. Extractives are formed mainly in the radial parenchyma, but the axial (longitudinal) parenchyma also can form them. Peroxidase activity increased markedly at the periphery of the heartwood (Dietrichs 1964; Lairand 1963), as did the activities of amylase (Höll 1972), phenol oxidases, malate dehydrogenase, etc. (Ziegler 1967).

Extractives accumulate in the lumen, or occlude or encrust pits and walls (Bauch et al. 1968; Fengel 1970; Krahmer and Côté; Krahmer et al. 1970). In some species, phenolic substances can diffuse from the ray parenchyma cells into the walls and lumens of fiber (Fengel 1970). Gas liquid chromatography and microspectrophotometry, capable of detecting relative amounts of extractives in cell walls and lumens (Bland and Hillis 1969; Krahmer et al. 1970) are useful, since toxic components probably convey greater durability if present in the cell wall than when in the lumen.

Generally, the amount of extractives increases from the pith to the heartwood periphery. Anderson et al. (1963), Rudman (1965), and others have shown that the toxicity of heartwood extractives to fungi and insects can decrease with age (Kumar 1971; Scheffer and Cowling 1966). This could be due to enzymic oxidations (Lry 1962; Shain and Mackay 1973), free radical reactions, polymerization, hydrolysis, and changes caused by acid and microbiological degradation. Extractives differ widely in toxic or repellent properties to different wood-destroying microorganisms (Merrill 1970; Scheffer and Cowling 1966). Mildly toxic components, if present in adequate amounts, can confer durability (Hart and Hillis 1972).

Mechanism of formation of heartwood and extractives.[2]—The relatively abrupt change of sapwood to heartwood reflects an active situation. The change is widely considered to be a DNA-coded aging effect influenced to some extent by enviroment. The erratic and undulating heartwood boundaries that cross growth rings in many trees, however, are not fully understood; probably most of these undulations are attributable to injury-altered wood, not heartwood. The narrow transition zone (when present) or the heartwood periphery are dynamic zones in the living tree, suggesting that heartwood formation is preceded by a period of increased matabolic activity (Chattaway 1952).

Some direct evidence of increased metabolic activity has been found at the heartwood periphery (Lairand 1963; Matsukuma et al. 1965; Zelawski 1960), but other studies do not confirm this. Hirai's (1951) finding that heartwood forms mainly during cambial dormancy suggests some lack of activity could be due to sampling at inappropriate periods. Other workers have suggested that both the Krebs cycle and pentose shunt enzymes were affected (Higuchi et al. 1967; Hillis 1964; Hillis and Inoue 1966; Ziegler 1967).

Heartwood extractives are formed during the dormant season from translocated or stored carbohydrates at the heartwood periphery or in the transition zone. Ethylene apparently plays a key role in the process; whether ethylene formation is triggered by water stress, suggested as a key factor in heartwood formation (Rudman 1966; Zycha 1948), remains to be determined. Peroxidase, whose activity increases at the heartwood periphery (Lairand 1963; Wardrop and Cronshaw 1962), and the phenol oxidases in the heartwood (Dietrichs 1964; Kondo 1964), can both darken tissues after exposure to air.

Ethylene may also play a role in the formation of fungus-related discolored wood. Some fungi produce ethylene; whether discolored wood is associated exclusively with these ethylene producing fungi has not been determined. Discolored wood may differ in composition from heartwood in the same tree.

Ethylene increases, in a short period, DNA and protein synthesis (Marei and Romani 1971) and the activity of the in-place synthesis of a number of enzymes. Those so far reported include phenylalanine ammonia lyase (PAS) (Hyodo and Yang 1971; Rhodes and Wooltorton 1971), polyphenol oxidase (Stahmann et al. 1966), α-amylase (Bashman 1966), cellulase (Abeles and Leather 1971), and, particularly, peroxidase (Imaseki 1970; Ridge and Osborne 1970). Several cases are known in which ethylene increases the rate of respiration (Hulme et al. 1971; Reid and Pratt 1972).

An association between auxin and formation of heartwood extractives has been considered (Hillis 1968; Ziegler 1967). The balance between auxin and eythlene may be more important than absolute amounts of either (Burg 1968; Mapson and Hulme 1970).

Distinguishing heartwood from sapwood.—In many species of southern hardwoods it is difficult to distinguish heartwood from sapwood, even with the aid of a microscope. Chemical indicators are useful on the southern oaks. Stearns and Hartley (1952) recommend use of the acidity indicator **Benzo Yellow** to distinguish heartwood from sapwood of green or dry oaks. **Dimethyl Yellow** and **Methyl Orange** are reportedly satisfactory for distinguishing sapwood of European and American oaks, but are unreliable on Japanese oaks (Anonymous 1957); a few drops of Dimethyl Yellow reagent brushed on the smoothed surface of oak wood normally give a red color to heartwood and a yellow shade to less acid sapwood.

Sapwood of red oak species is more permeable than heartwood (chapter 8); this characteristic has been used by Womeldorff (1965) to separate red oak chips of the two tissues. In his tests, air-dry chips of sapwood soaked in water sank more quickly than those of heartwood; when the chips were redried in air for a week and re-soaked in water, time to sink increased but remained less for sapwood than for heartwood as follows:

Trial and tissue	Small chips	Medium chips	Large chips
	Minutes elapsing before sinking		
Initial Impregnation			
Sapwood	50	68	198
Heartwood	311	541	1,878
Reimpregnation			
Sapwood	143	300	410
Heartwood	490	1,375	1,806

When sapwood and heartwood chips of red oak species were placed in a suction flask half full of water, stoppered, and aspirator vacuum of 29.5 psi applied, it was found that the chips floated continuously during evacuation, but sapwood chips would sink on removal of the vacuum after the following treatment periods:

Chip size	Time of applied vacuum
	Seconds
Small	10
Medium	15
Large	20

In both of these experiments, chip length was constant at 1/2 inch; small, medium, and large chips measured 3/8-, 5/8-, and 3/4-inch tangentially (Womeldorff 1965).

Keith (1977) proposed the use of differential drying of green cross-sections to distinguish heartwood from sapwood. A commercial heat gun is used and the heartwood will show up as a dry zone due to the lower permeability.

Few data are published on differences in the mechanical properties of heartwood and sapwood. Baker (1970) found no significant difference in toughness between heartwood and sapwood of white ash. However, Shigo (1975) states that the ash species do not have true heartwood so these results may not be relevant.

Differences between heartwood and discolored wood with which it is often confused have been summarized by A.L. Shigo, as follows (see also subsection DISCOLORED WOOD under sect. 9-1 and figs. 9-5 through 9-10):

Heartwood	Discolored wood
Process initiated by aging	Process initiated by wounds.
Internal stimuli	External stimuli.
Proceeds centrifugally	Proceeds centripetally.
New tissues affected each year	Tissues that form after wounding are seldom affected.
Oldest tissues affected first	Youngest tissues affected first.
No hard rim at margin of white wood	Hard rim between discolored wood and white wood.
Intermediate zone between heartwood and white wood	No intermediate zone between discolored wood and white wood.
In ring-porous species summerwood colored mostly	Springwood and summerwood colored.
Color mostly in cell walls	Color in walls and cell contents.
Continous	In columns.
Throughout tree	Depends on wounds.
Disrupted about wounds	Forms first about wounds.
Stabilized	First stage of a process that can develop further.

Heartwood	Discolored wood
Mostly in ring-porous species	In all species.
Checks radially	Honeycomb checks, and around rings.
pH not high	pH high in advanced stages.
Moisture not high	Moisture high in advanced stages.
Mineral content not high	Mineral content high in advanced stages.
Cylinders of heartwood not pointed at ends	Column of discoloration pointed at ends.
Usually circular in cross-section	Circular or any other configuration.
Discolors when wounded	Does not discolor further when wounded.
No microorganisms	Microorganisms present as the processes continue.
Electrical resistance higher than healthy sapwood	Electrical resistance lower than contiguous healthy wood.

Heartwood and sapwood proportions of volume.—In some species (e.g., sweetgum), colored wood is prized, and in others white wood commands the highest price (e.g., hickory). These value differences cause users to be interested in proportions of colored wood and white wood and heartwood and sapwood.

The proportion of heartwood contained in hardwood stems varies within trees, within species, and among species. Table 5-2 presents some data on average width of sapwood in selected southern hardwoods of veneer-log size. Examination of 6-inch hardwoods from southern pine sites indicates that heartwood percentages in such trees are greatest in white oak, yellow-poplar, and post oak; they are least or absent in true hickory, hackberry, red maple, and the ashes (fig. 5-16).

In some species, the condition and color of stem bark is an indicator of colored wood volume, but not necessarily heartwood volume. Colored wood content in sweetgum, which may start formation at ages from 20 to 70 years in stems from 3 to 18 inches in diameter, can be estimated from tree appearances. Sweetgum trees with high colored wood content are characterized by bark with flattened ridges and reddish hue; development of red-colored wood in sweetgum is believed to progress most rapidly in injured trees that are slowly dying (Putnam 1928).

In white oak, McGinnes and Shigo (1975) found that true heartwood formation was retarded by wounds (table 5-3).

In hickory species, the greatest proportion of white sapwood is found in rapidly growing second-growth trees; for example, 9-inch trees with 7-11 rings per inch had 3.6-inch-wide sapwood, while slower growing 16- to 23-inch trees with 15-33 rings per inch averaged only 2.0-inch-wide sapwood (Paul 1929).

Percentage of heartwood in yellow-poplar stems is inversely proportional to height above ground. At stump height, six trees sampled in the Piedmont section of North Carolina showed heartwood percentage (of bark-free cross section) of about 65 percent; at 60 feet, the heartwood proportion was only about 45 percent (fig. 5-17).

Similar observations on other species of interest are not yet reported in the literature.

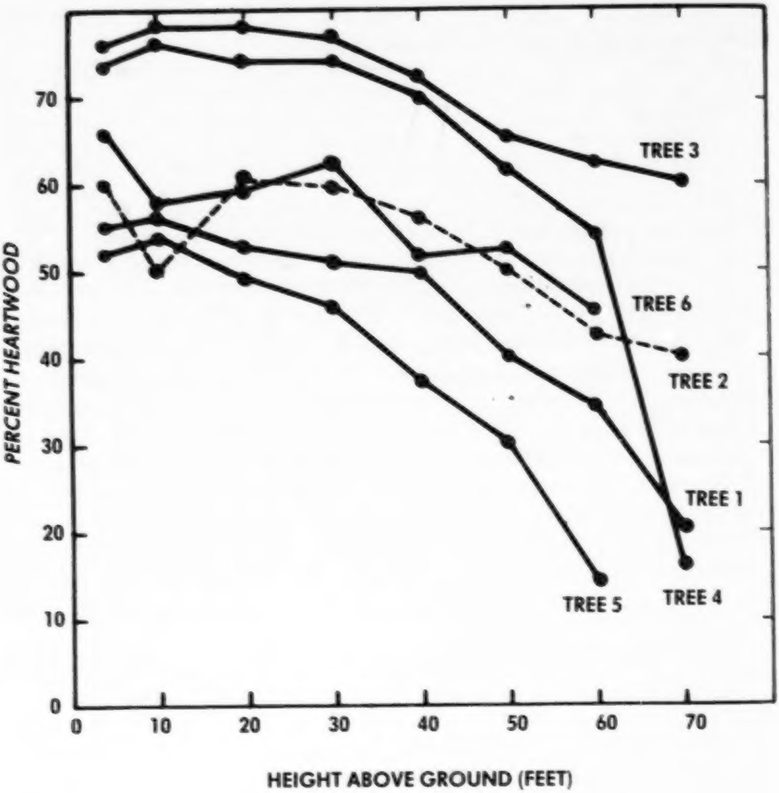


Figure 5-17.—Percentage of heartwood in bark-free stemwood of yellow-poplar related to height above ground. (Drawing after Taylor 1968a.)

TABLE 5-3.—*Average number and range of rings of sapwood plus average ring width for 10-year periods before and after injury in 1951 at three height levels for Missouri-grown white oaks (McGinnes and Shigo 1975)*

Statistic	For 10 control trees			For 15 injured trees[1]		
	1 meter	2.5 meters	5 meters	1 meter	2.5 meters	5 meters
Sapwood rings in 1961 (number)						
Average[2]	12	11	10	16	15	15
Range	9-21	7-17	8-15	10-22	10-21	10-21
Average ring width (mm)						
1942-1951	2.67	1.91	2.20	1.81	1.41	1.83
1952-1961	2.13	1.56	1.85	2.45	1.43	1.68

[1] Trees were frilled with deep axe cuts completely encircling the base of the tree and 2, 4, 5-T in fuel oil was applied to the frills.

[2] Differences between control and injured trees were significant (5 percent level) at all three heights.

FIGURE IN WOOD

One of the charms of wood is the variability of its appearance. The patterns that appear on the surface of wood are attributable to the nature of woody tissue, variations in color **pigmentation** (see sect. 9-1), **luster** (light reflectivity), **grain** (arrangement and direction of cellular alignment), **texture** (fine or coarse, depending on size and proportions of cells), and patterns made by insect or fungal attack. Collectively these patterns are termed **figure** in wood (figs. 5-18 and 5-20 illustrate some of these figures). Because of the small size of hardwoods growing on southern pine sites, their utilization in wall paneling and furniture is somewhat limited. Figure, therefore, is of less importance in their utilization than in utilization of larger bottomland hardwoods.

Visibility of normal grain configuration can be accentuated by machining to expose radial or tangential surfaces; ashes, elms, oaks, and hackberry have easily discernible grain patterns (figs. 5-4, 5-5, 5-6 top, 5-7 bottom, through 5-13 top). Ring-porous woods, or woods with pronounced growth-ring margins from parenchyma or flattened fibers, and those with conspicuous rays usually show recognizable figures resulting from normal tissue patterns (figs. 5-4 through 5-15).

Ribbon or stripe figure.—Ribbon or stripe figure results from interlocked grain (fig. 5-18 right); it appears on the radial surface of wood in which reversal of spiral grain takes place at uniform intervals of a few years. When the resulting interlocked grain is quarter-cut, the alternating angularity of the cells alters the reflecting qualities of alternate zones and gives each zone an apparently different color, thus forming a ribbon figure. The interlocked and alternately inclined grain presents a machining problem because it is difficult to machine a radial face longitudinally without causing chipped grain in alternate stripes.

Interlocked grain is typical of black tupelo, the elms, and—to a lesser extent—of sweetgum. Webb (1969) found from study of 180 sweetgum trees grown from Virginia to Florida that all had interlocked grain to some degree. The average spirality was 12° and the extreme was about 30° in alternate directions. Degree of interlocked grain varied significantly within stands (fig. 5-19), but was not correlated with growth rate or geographic location (Webb 1969).

Bird's-eye figure.—Red maple, yellow-poplar, and the ashes sometimes develop **bird's eye figure,** i.e., cone-shaped distortions of the growth increments (fig. 5-20 right). The distortions appear under the surface of the bark as conical depressions in the tangential surface of the wood and may persist for a number of years or even for the life of the tree. The distortion may occur in a limited area or series of areas on one side of the stem or, less commonly, throughout the entire tree. The figure is developed by cutting rotary veneer or flat-sawn lumber from the tangential face. The machining of such stock requires special care because of chips splitting out below the line of planer knives.

Wavy and curly grain.—The ashes and red maple may also exhibit a corrugated aspect when split in the radial plane (fig. 5-18, left). In contrast with the longitudinal zones caused by interlocked grain, the corrugations that form **wavy**

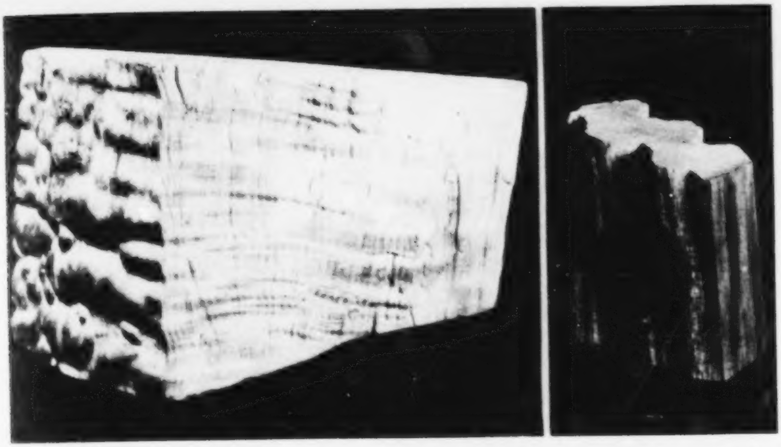


Figure 5-18.—Figure in wood. (Left) A maple block with blister figure on the tangential surface and wavy grain on the radial surface. When smoothed, these surfaces will reflect light to give these figures. (Right) Wood with interlocked grain split longitudinally along a radial plane. Smoothed radial surface will show typical ribbon (stripe) figure common to the elms and black tupelo. (Photos from W.A. Côté.)

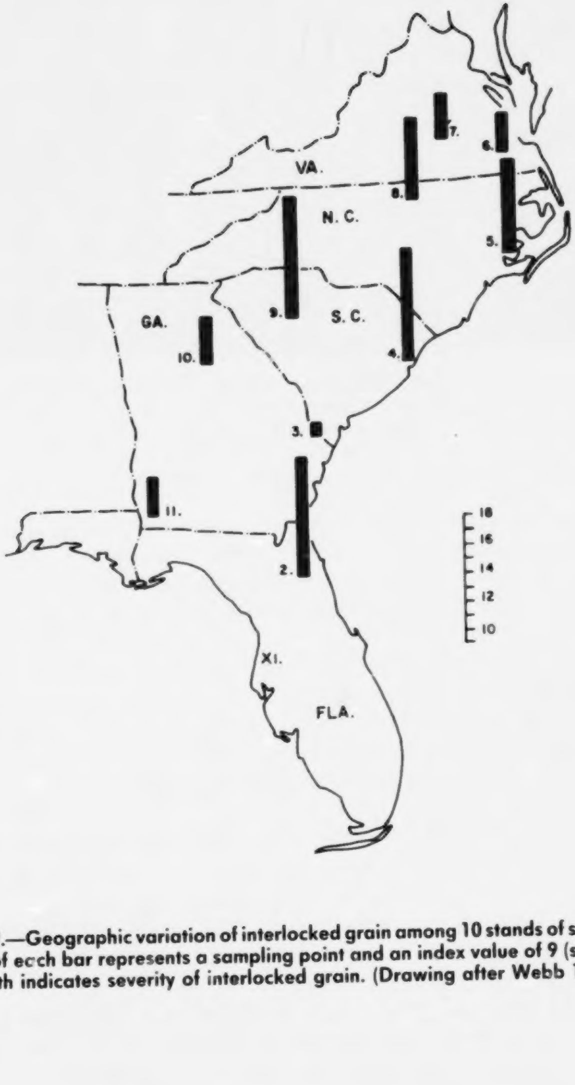
or **curly** grain are oriented so that the long axis of each corrugation runs from the bark inward toward the pith. As is the case with the tangentially exposed bird's-eye figure, the radially exposed tangential undulations of wavy grain persist year after year, with the slope of the fibers remaining the same in successive growth increments.

Fiddle-back grain.—When the corrugations of the wavy figure are closely spaced and the fiber curvature is abrupt, the pattern is known as a **fiddle-back** figure. The radial face of stock exhibiting this figure is prone to develop chipped and torn grain in the process of machining. Occasionally, in yellow-poplar and maple, zones of tissue will undulate in the tangential plane to form a blister figure (fig. 5-18 left).

Pigment figure.—A flame-like effect, **pigment figure,** in sweetgum heartwood due to irregular streaks and patches of darker color is sometimes prominent and attractive (fig. 5-20 left); these color patterns and their causes are reviewed by Davis and Beals (1977) and by Putnam (1928). Less appreciated, but still interesting, are the color streaks in yellow-poplar and soft maple—the latter usually associated with insect attacks.

Partridge wood.—Oak sometimes displays a figure called **partridge wood** resulting from rot by the fungus *Stereum frustolosum* (Pers.) Fr. The wood takes on a dark coloration interspersed with spindle-shaped pockets lined with white mycelium. For maximum color conrast, the wood should be left unfinished, although wiping stains can produce pleasing effects (Walters 1970).

Readers wishing to further study figure in wood will find the following references useful: Bailey (1948); Jane (1970); Panshin and deZeeuw (1980); Beals and Davis (1973, 1977); Hejnowicz and Romberger (1973); and Keller et al. (1974).


VA.
N. C.
GA.
S. C.
FLA.
1.
2.
3.
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X1.
18
16
14
12
10

Figure 5-19.—Geographic variation of interlocked grain among 10 stands of sweetgum. Bottom of each bar represents a sampling point and an index value of 9 (see scale); bar length indicates severity of interlocked grain. (Drawing after Webb 1964.)

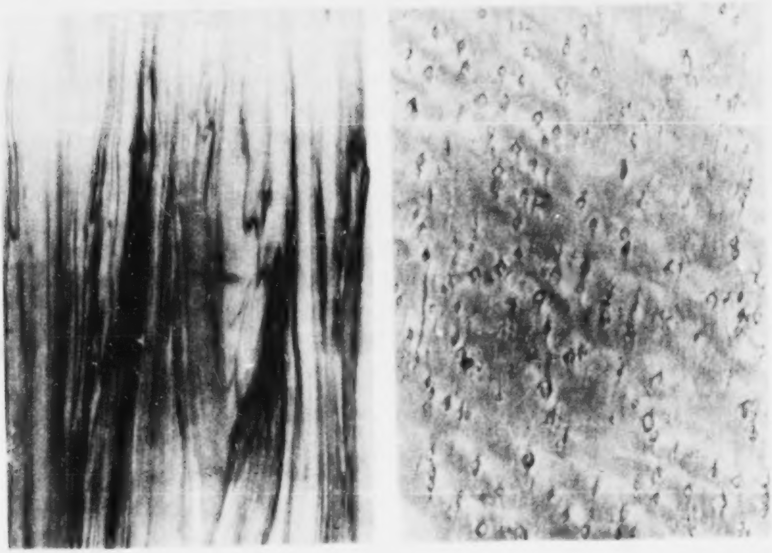

Figure 5-20.—Figure in wood. (Left) Figured sweetgum (redgum) resulting from pigmentation or irregular deposition of colored materials. (Right) Bird's-eye figure in maple. This figure is more common in hard maple but will occur in red maple. (Photos from W.A. Côté.)

5-2 INTRODUCTION TO MINUTE STRUCTURE

The tissues and cell types observable in a block of southern hardwood by light and scanning-electron microscopy are shown in figures 5-21, 5-22, and 5-23 through 5-45. Figure 5-1 diagrams the direction from which the cubes in figures 5-23 through 5-45 were viewed by a scanning electron microscope.[3] Hardwood consists principally of closely packed vertical longitudinal cells called **fibers** among which are interspersed larger, but thinner-walled longtudinal cells called **vessel elements** and, usually, longitudinal **parenchyma** cells. Associated are horizontal tissues called **rays,** extending radially toward the pith. The cells are interconnected through gaps in their secondary walls called **pits,** in most of which characteristic borders form **pit chambers.**

Figure 5-21.—Schematic three-plane drawing of the wood of sweetgum. (330X)
Surface A. 1-1^a, boundary between two annual rings (growth proceeding from right to left); 2-2^a, wood ray consisting of procumbent cells; 2^b2^c, wood ray consisting of upright cells; a-a^6 inclusive, pores (vessels in transverse section); b-b^4, inclusive, fiber tracheids; c-c^3, inclusive, cells of longitudinal parenchyma; e, procumbent ray cell.
Surface B. f,f^1, portions of vessel elements; g^1, portions of fiber tracheids in lateral surface aspect; h, a strand of longitudinal parenchyma in lateral surface aspect; 3-3^a, upper portion of a heterocellular wood ray in lateral sectional aspect; i, a marginal row of upright ray cells; j, two rows of procumbent ray cells.
Surface C. k, portion of a vessel element in tangential surface aspect; k^1,k^2, overlapping vessel elements in tangential surface aspect; 1, fiber tracheids in tangential surface aspect; 4-4^a, portion of a wood ray in tangential sectional view; m, an upright cell in the lower margin; n, procumbent cells in the body of the ray.
(From Textbook of Wood Technology, Vol. I, by A.J. Panshin and C. deZeeuw. 1980. Fourth Edition ^{c}, used with the permission of McGraw-Hill Book Company.)

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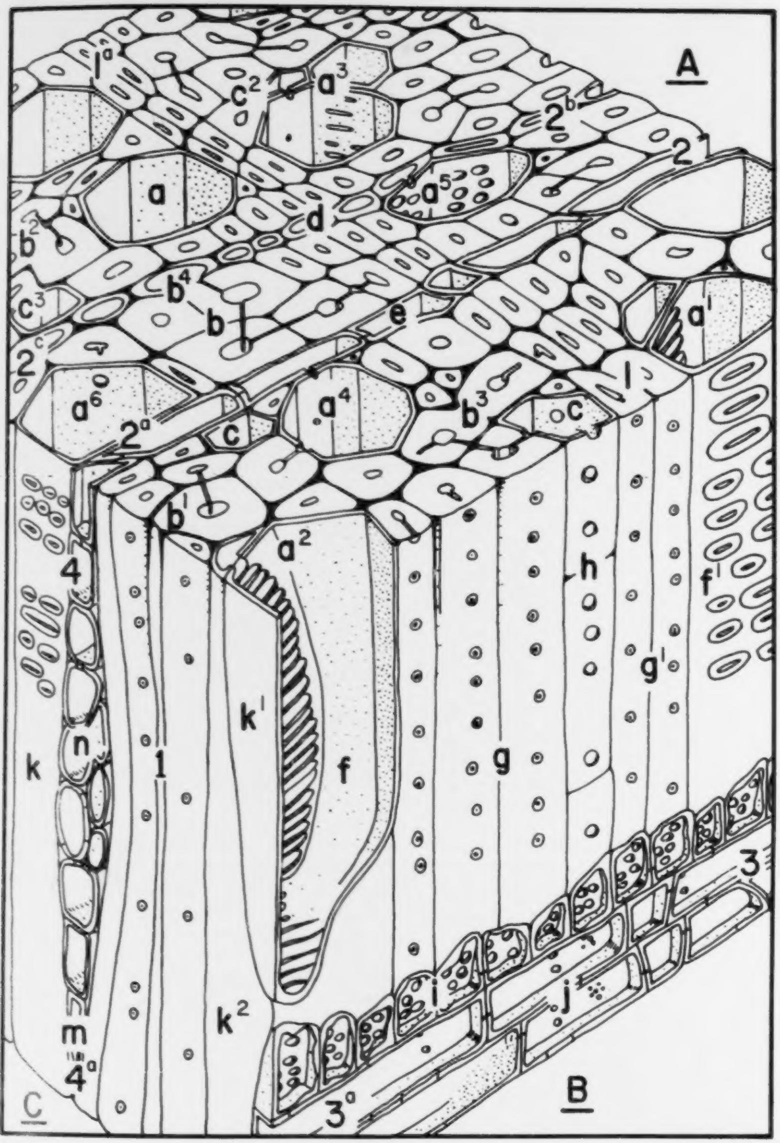
[3] For another atlas of scanning electron micrographs of these same species, but taken at slightly lower magnification, see McMillin and Manwiller (1980); the lower magnification affords better visualization of pore and parenchyma patterns.


A
1a
c2
a3
2b
2
a
a5
d
b2
b4
c3
b
e
a1
2c
l
a6
a4
b3
c
2a
c
4
b1
a2
h
f1
g1
k1
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n
1
g
f
3
i
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4a
C
B
3a

Figure 5-21.—

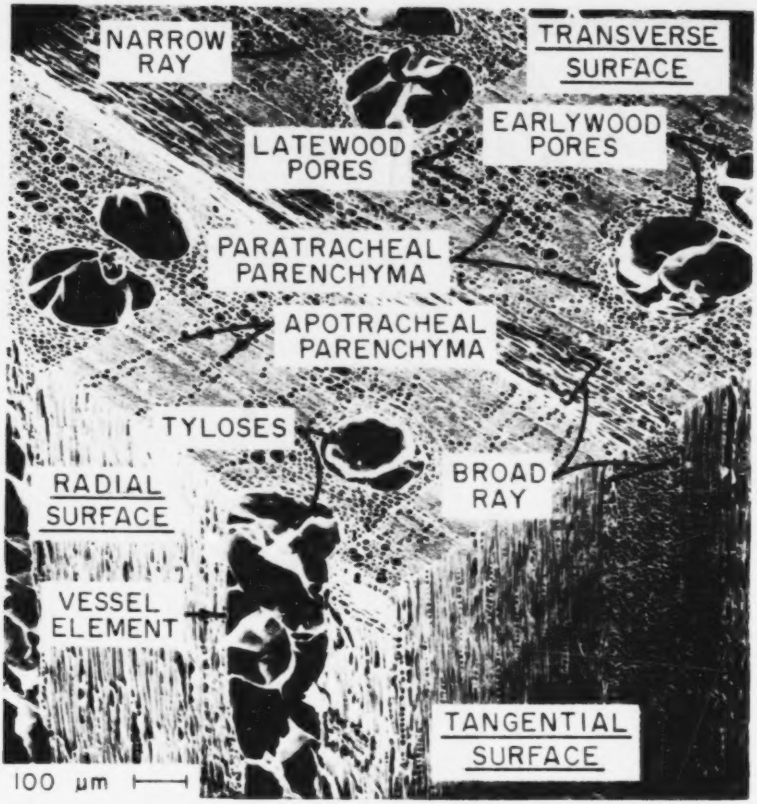
NARROW RAY
TRANSVERSE SURFACE
EARLYWOOD PORES
LATEWOOD PORES
PARATRACHEAL PARENCHYMA
APOTRACHEAL PARENCHYMA
TYLOSES
RADIAL SURFACE
BROAD RAY
VESSEL ELEMENT
TANGENTIAL SURFACE
100 µm

Figure 5-22.—White oak cube; for direction of view see figure 5-1B. Elements, tissues, and structures are labeled to assist in studying and identifying features in figures 5-23 through 5-45. A complete growth ring is visible. (Scanning electron micrograph from W.A. Côté.)

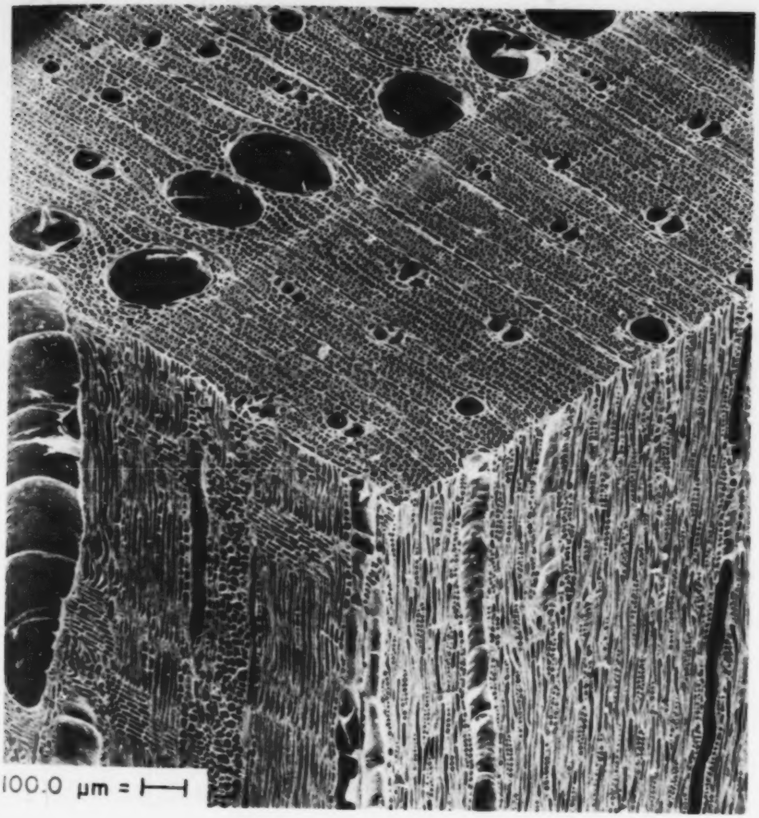

Figure 5-23.—Green ash, a ring-porous wood. The latewood pores are arranged in short, radial multiples that are sparsely distributed. Rays are small, normally spaced and uniform in size. The longitudinal parenchyma, difficult to identify in this view, are paratracheal, being associated with the latewood pores (vessels). A few tyloses are visible in the earlywood vessels. This wood is nearly identical anatomically with white ash (fig. 5-24). (Scanning electron micrograph from W.A. Côté.)

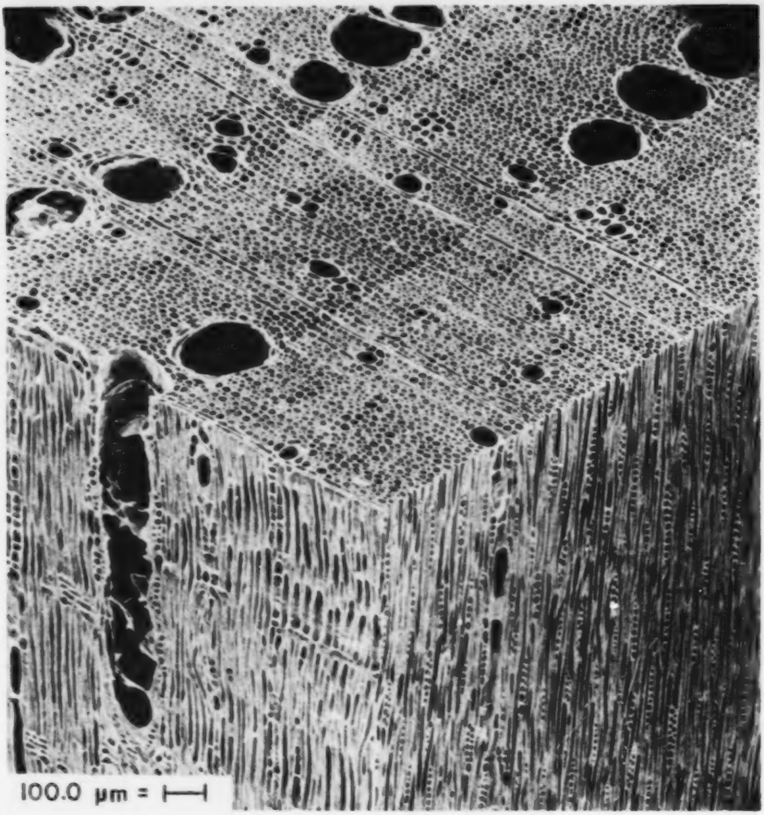

Figure 5-24.—White ash, considered identical anatomically with green ash. (See fig. 5-23 for description.) (Scanning electron micrograph from W.A. Côté.)

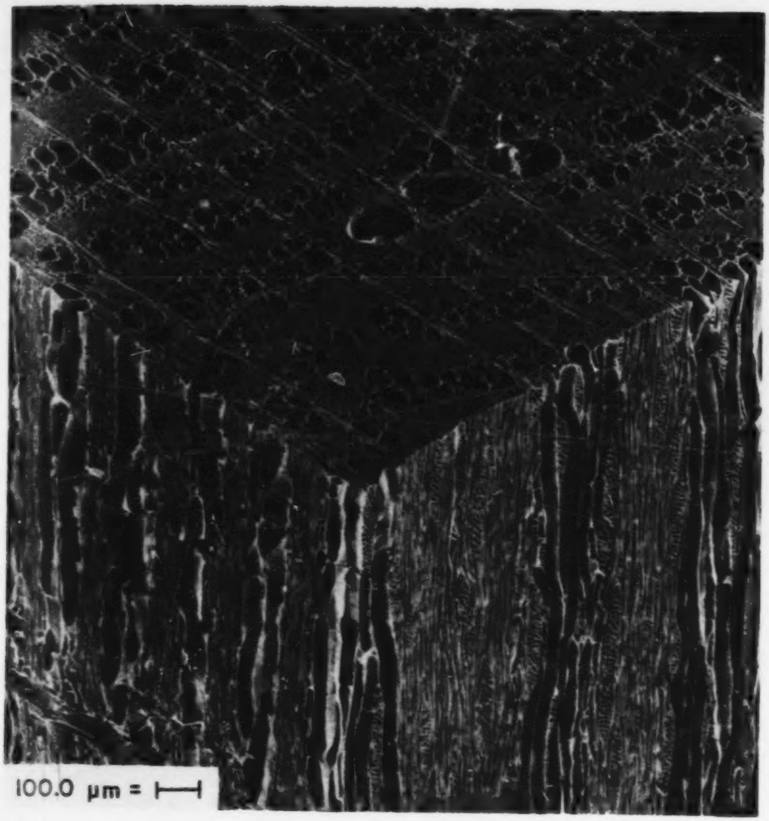

Figure 5-25.—American elm, a ring-porous wood. The latewood pores are arranged in an ulmiform (wavy, tangential bands) pattern. Rays are normally spaced and 3-4 seriate. The longitudinal parenchyma are paratracheal. Tyloses appear in two earlywood vessels in the center of the picture. (Scanning electron micrograph from W.A. Côté.)

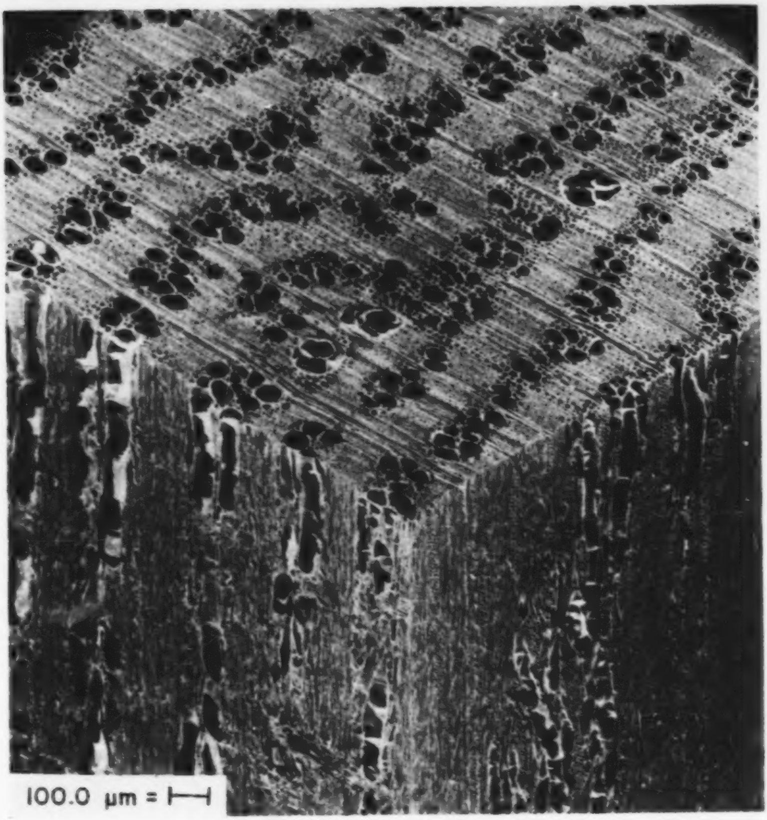

Figure 5-26.—Winged elm, a ring-porous wood very similar to American elm (fig. 5-25). Winged elm usually has a more interrupted, uniseriate row of earlywood pores (vessels) at the start of the growth ring. (Scanning electron micrograph from W.A. Côté.)

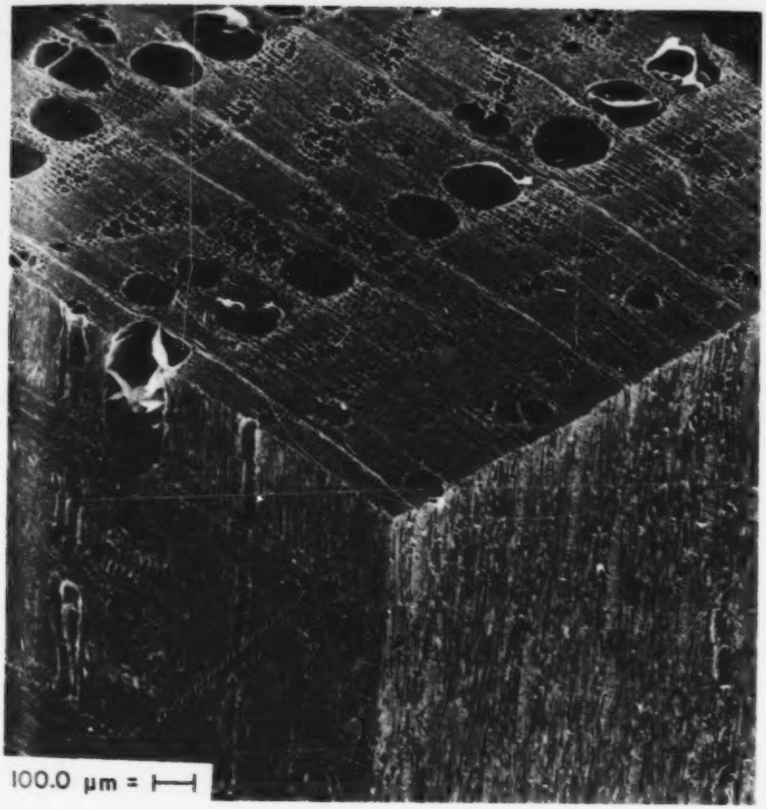

Figure 5-27.—Hackberry, a ring-porous wood. The latewood pores (vessels) are in an ulmiform arrangement. The rays are normally spaced and relatively conspicuous. Longitudinal parenchyma are paratracheal, being intermixed with latewood vessels and vascular tracheids. A few tyloses are evident in the earlywood vessels. (Scanning electron micrograph from W.A. Côté.)

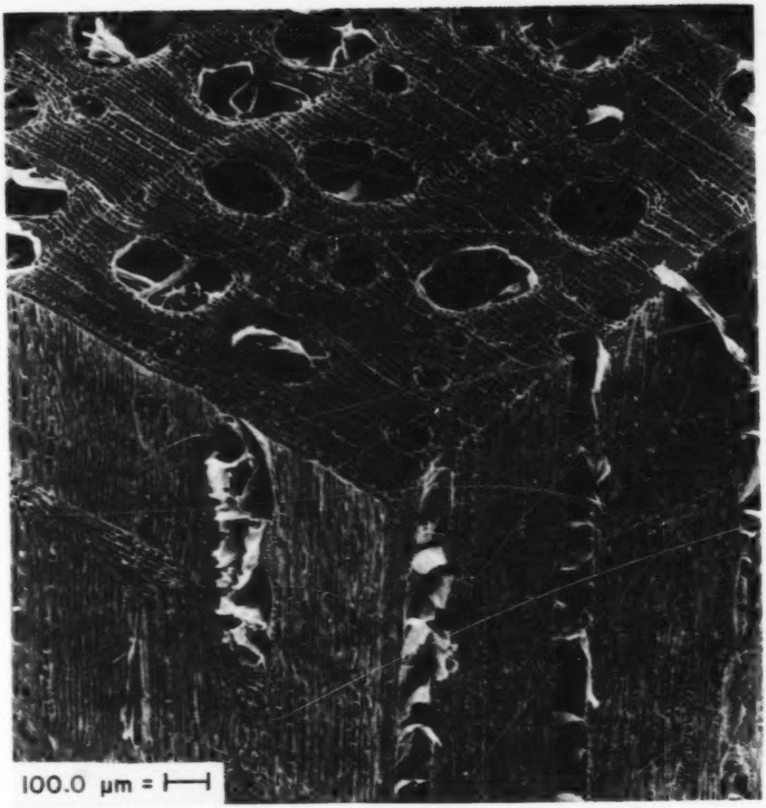

Figure 5-28.—True hickory, a ring-porous wood. The latewood pores (vessels) are solitary and in short, radial multiples sparsely distributed. Rays are normally spaced and uniform. Longitudinal parenchyma are essentially apotracheal, forming short tangential bands at right angles to the rays. Tyloses are fairly abundant. (Scanning electron micrograph from W.A. Côté.)

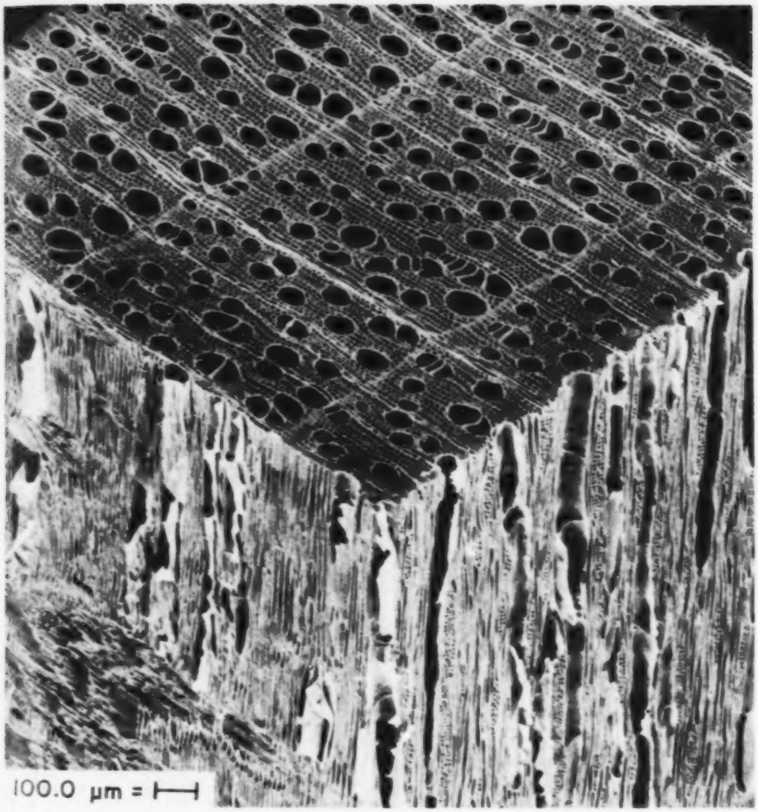

Figure 5-29.—Red maple, a diffuse-porous wood. The pores (vessels) are solitary or in radial multiples evenly distributed within the growth ring. Rays are normally spaced and variable in size. Longitudinal parenchyma are marginal, defining growth ring boundaries and intermixed with fibers. Tyloses are normally absent, but present in this specimen. (Scanning electron micrograph from W.A. Côté.)

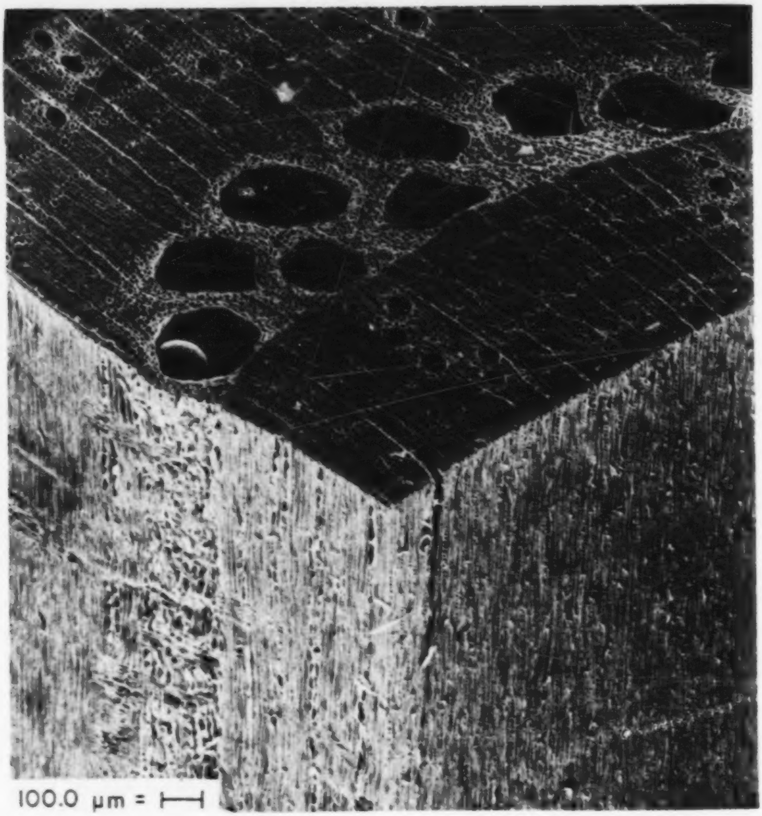

Figure 5-30.—Black oak, one of the red oak group of woods not distinguishable as to species. Members of the group are ring-porous, the earlywood pores (vessels) in two or more rows. Latewood pores have a dendritic arrangement (groups that are oblique or in echelon) and are surrounded by paratracheal parenchyma. Individual pores are solitary, rounded, sparsely distributed, and have thick walls. Rays are either uniseriate or broad (oak type). The extremely broad rays are the most important anatomical feature of oak woods. Broad rays are absent in this figure but may be seen in figures 5-31, 5-32, and most of the remaining figures of oaks. Longitudinal parenchyma are abundant as paratracheal and apotracheal banded parenchyma. Tyloses usually are sparse to absent in the red oak group. (Scanning electron micrograph from W.A. Côté.)

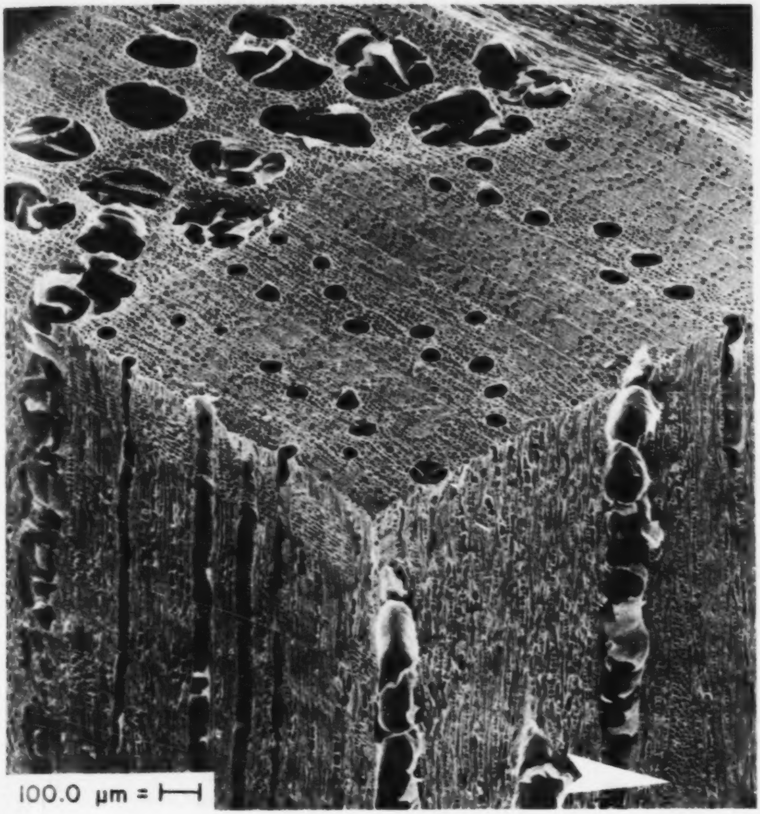

Figure 5-31.—Blackjack oak, one of the red oak group of woods; the description given for black oak (fig. 5-30) applies. Exceptions in this microgrpah are the abundance of tyloses and the presence of broad rays in tangential (arrow) and transverse views. (Scanning electron micrograph from W.A. Côté.)

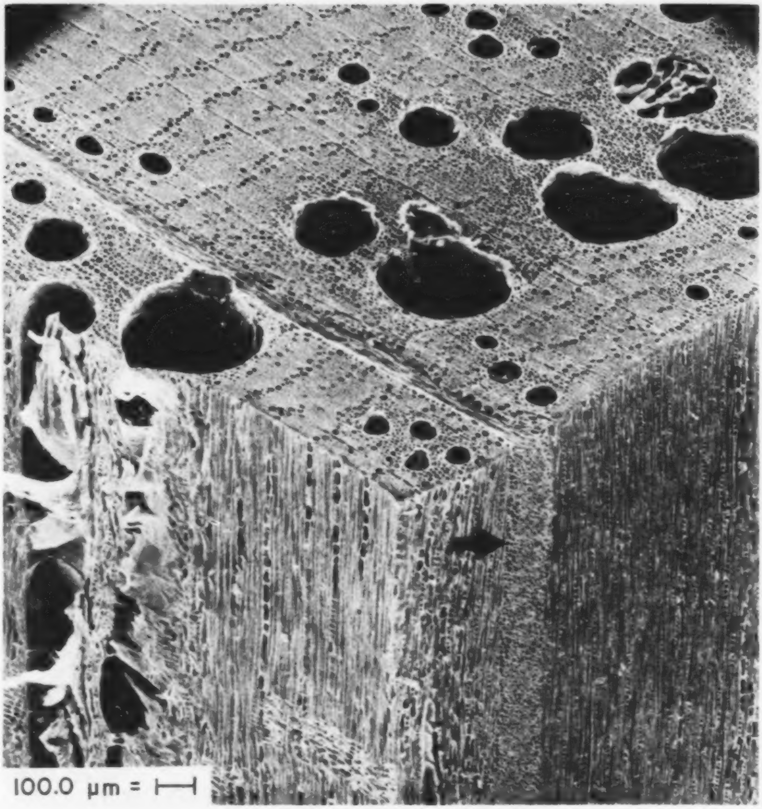

Figure 5-32.—Cherrybark oak, one of the red oak group of woods; the description given for black oak (fig. 5-30) applies. A broad ray is visible near the corner of the cube (arrow). (Scanning electron micrograph from W.A. Côté.)

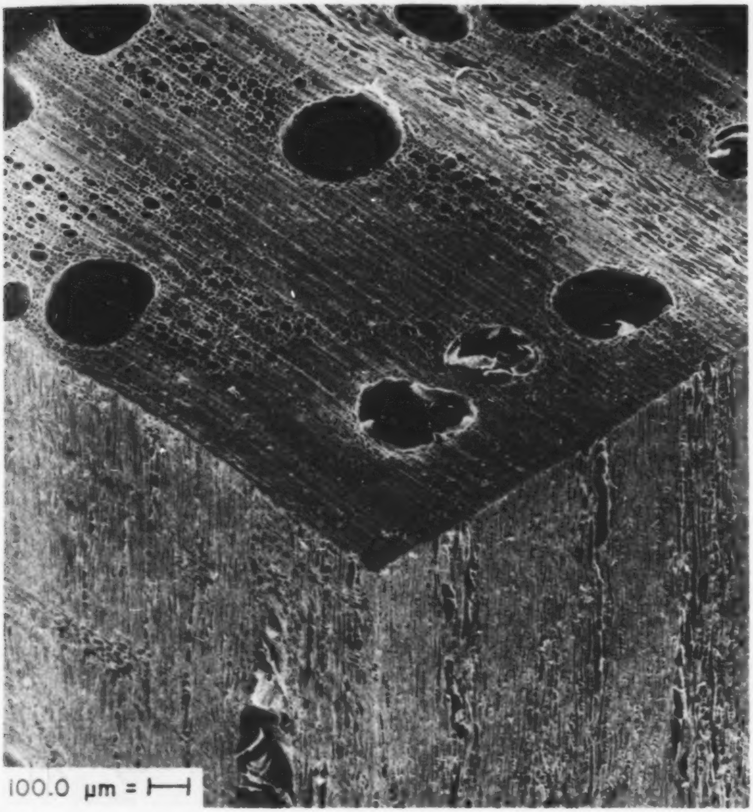

Figure 5-33.—Chestnut oak, one of the white oak group of woods not distinguishable as to species. Members of the group are typically ring-porous, the earlywood pores (vessels) in several rows. Latewood pores have a dendritic arrangement (radially oblique or in echelon on transverse surface) and are surrounded by paratracheal parenchyma. Individual latewood pores are solitary, angular, very small, closely spaced and thin walled. Rays are either uniseriate or broad (oak type). Tyloses usually are frequent and are most abundant in white oak (fig. 5-41). The white oaks are separable from the red oaks (see key), the most important criterion being the appearance of the latewood pores. (Scanning electron micrograph from W.A. Côté.)

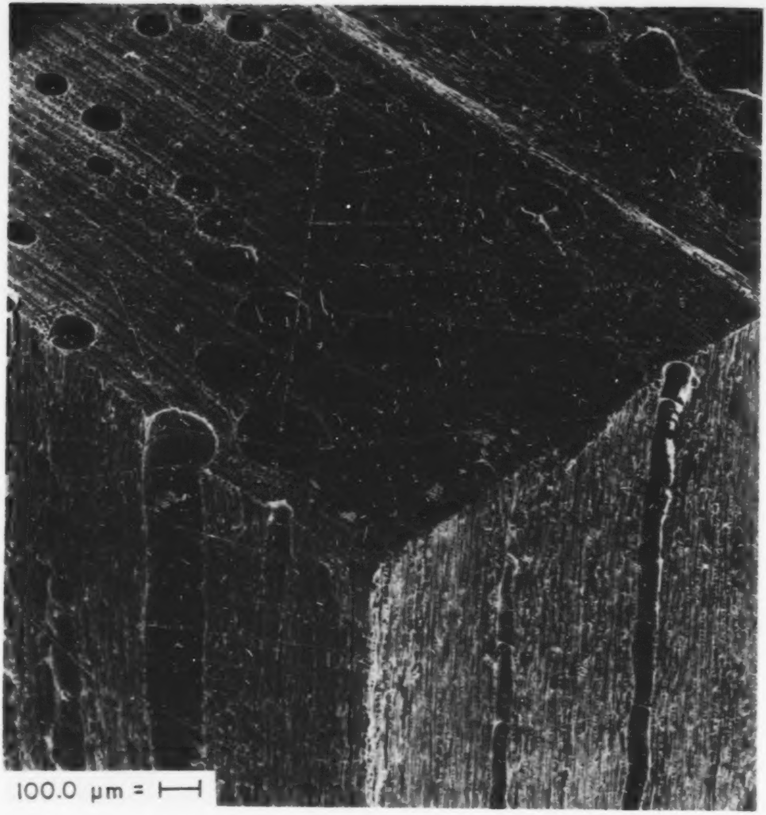

Figure 5-34.—Laurel oak, a member of the red oak group (see fig. 5-30 for description). This sample exhibits a gradual transition in pore size (semi-ring-porous) that is more common in the red oaks than in the white oaks. (Scanning electron micrograph from W.A. Côté.)

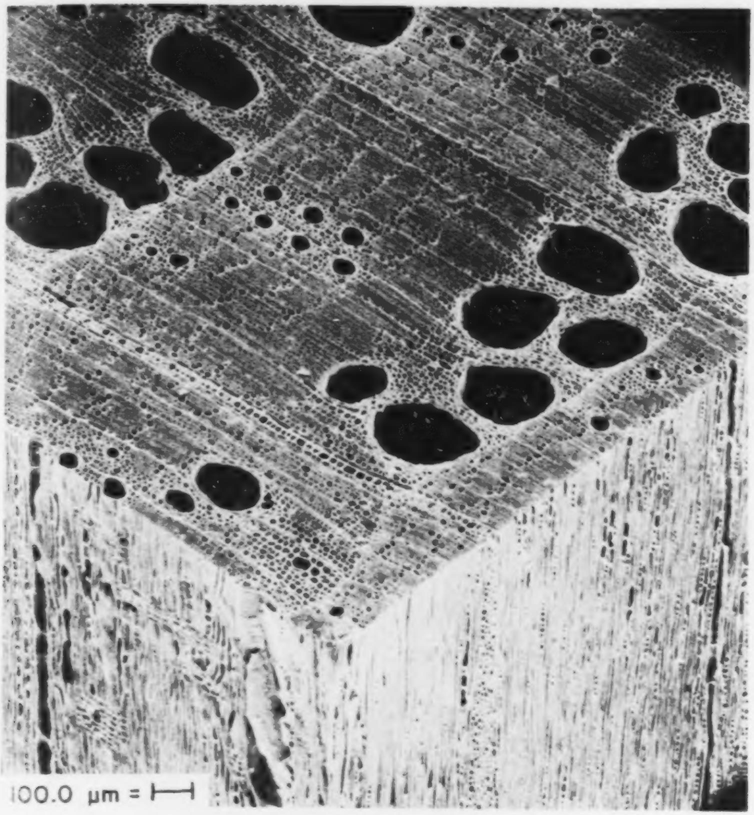

Figure 5-35.—Northern red oak, a member of the red oak group (see fig. 5-30 for description). Note absence of tyloses and the rounded, sparsely distributed latewood pores. (Scanning electron micrograph from W.A. Côté.)

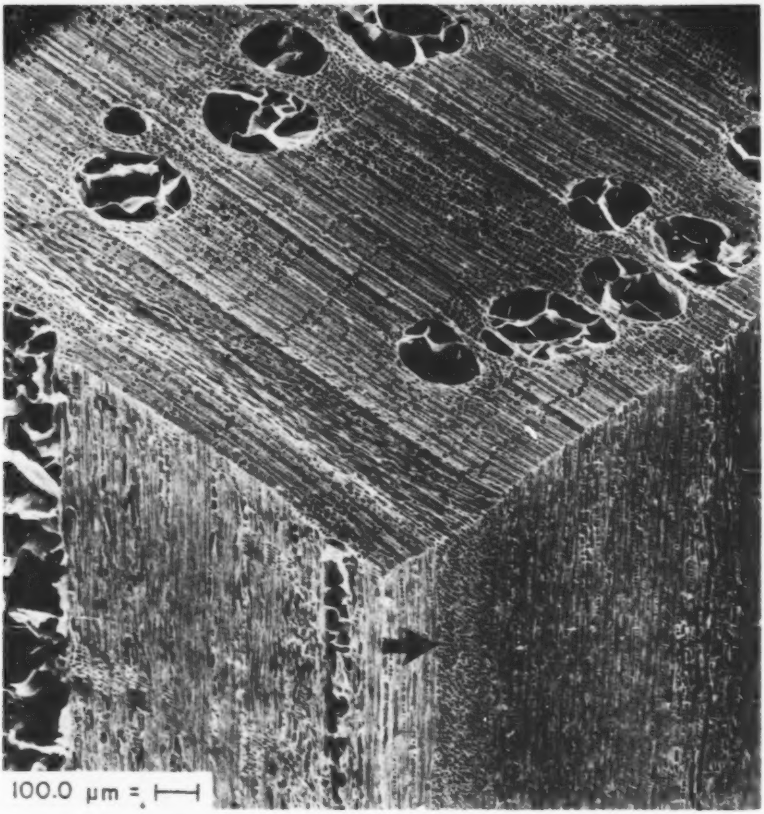

Figure 5-36.—Post oak, a member of the white oak group (see fig. 5-33 for description). Note abundance of tyloses in the earlywood vessels and the numerous, small latewood pores. A broad ray is visible near the corner of the cube (arrow). (Scanning electron micrograph from W.A. Côté.)

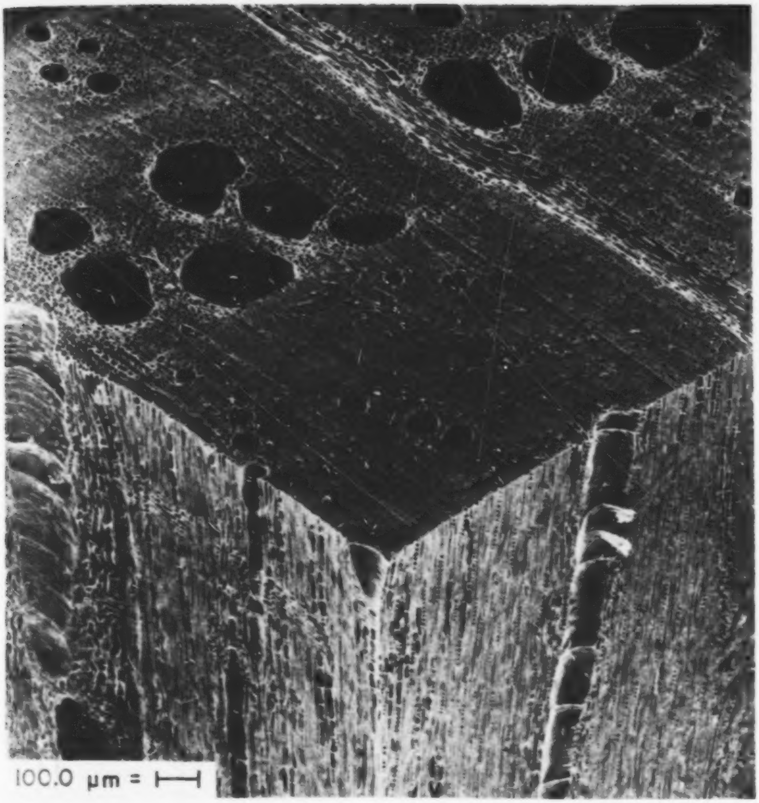

Figure 5-37.—Scarlet oak, a member of the red oak group (see fig. 5-30 for description). (Scanning electron micrograph from W.A. Côté.)

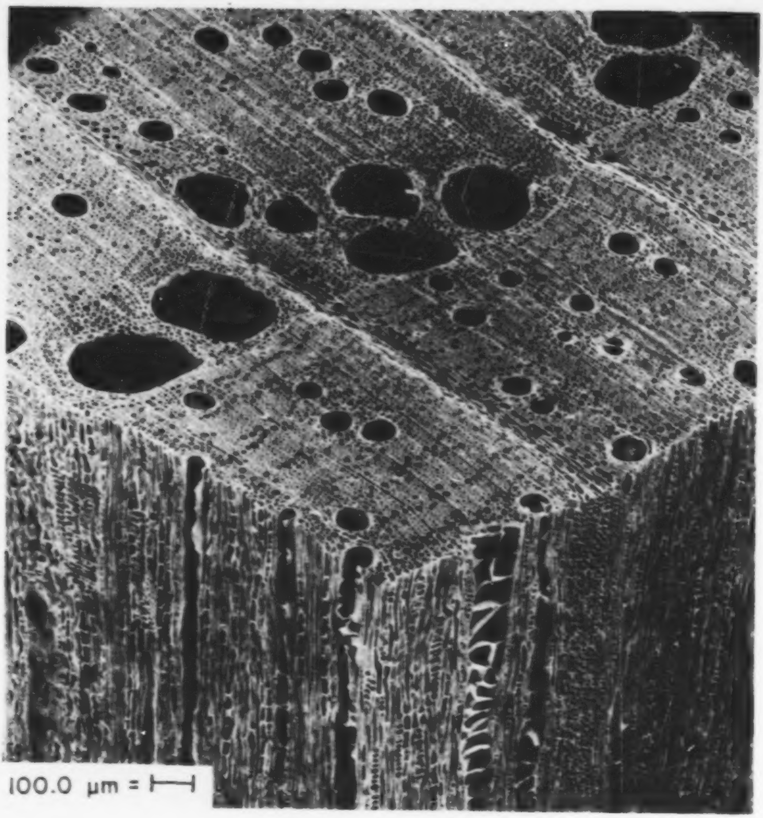

Figure 5-38.—Shumard oak, a member of the red oak group (see fig. 5-30 for description). (Scanning electron micrograph from W.A. Côté.)

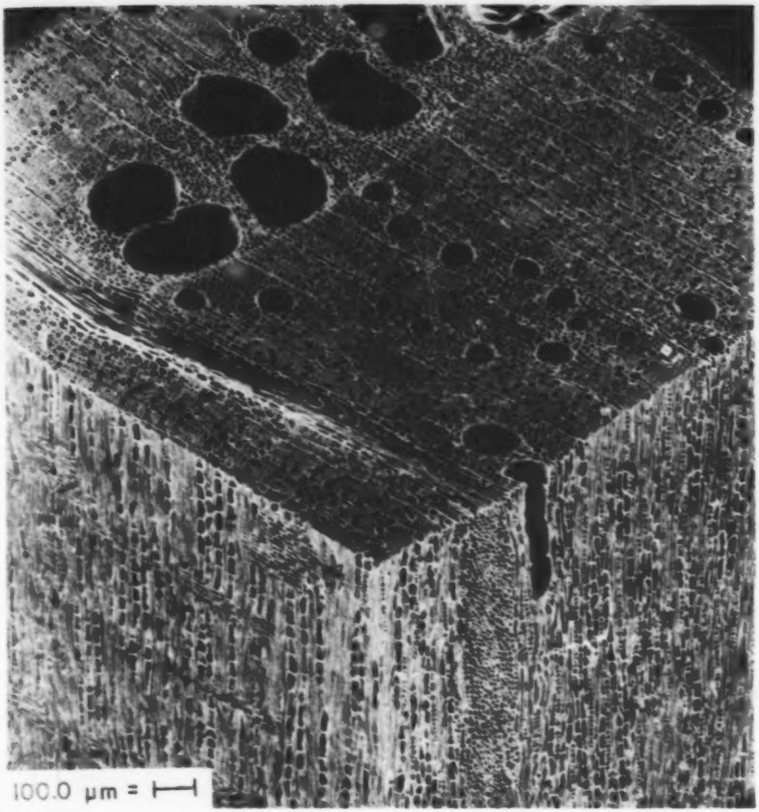

Figure 5-39.—Southern red oak, a member of the red oak group (see fig. 5-30 for description). A broad ray can be seen near the corner of the cube. Note rounded, thick-walled, sparsely distributed latewood pores; compare with white oak, fig. 5-41. Visible on the transverse section are seven large earlywood vessels and about 19 latewood vessels; additionally, abundant longitudinal axial parenchyma cells appear as small circular black pores on the transverse surface. (Scanning electron micrograph from W.A. Côté.)

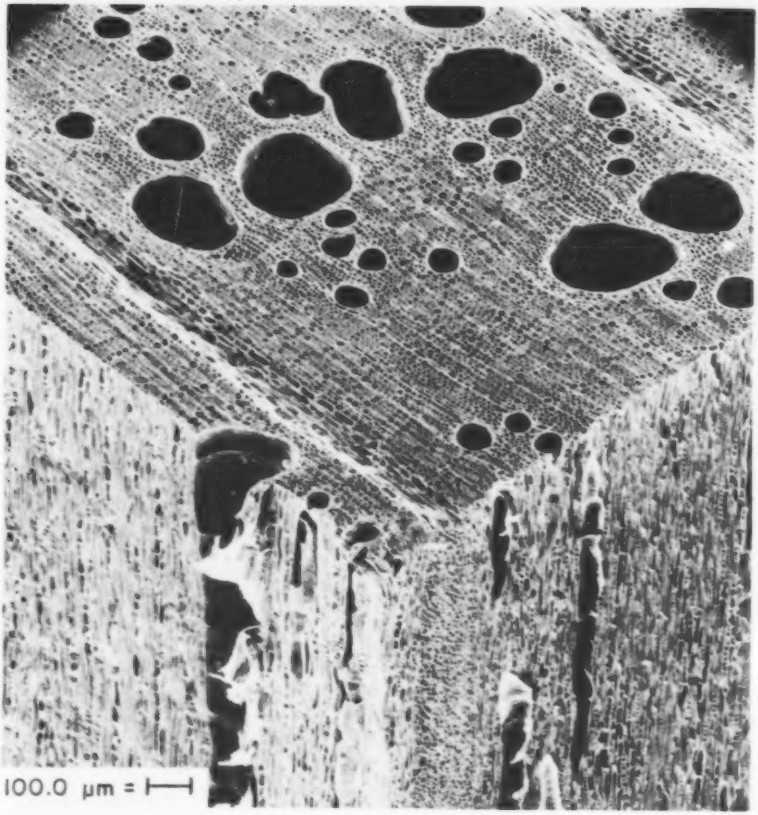

Figure 5-40.—Water oak, a member of the red oak group (see fig. 5-30 for description). Broad rays are present at top right and lower left. (Scanning electron micrograph from W.A. Côté.)

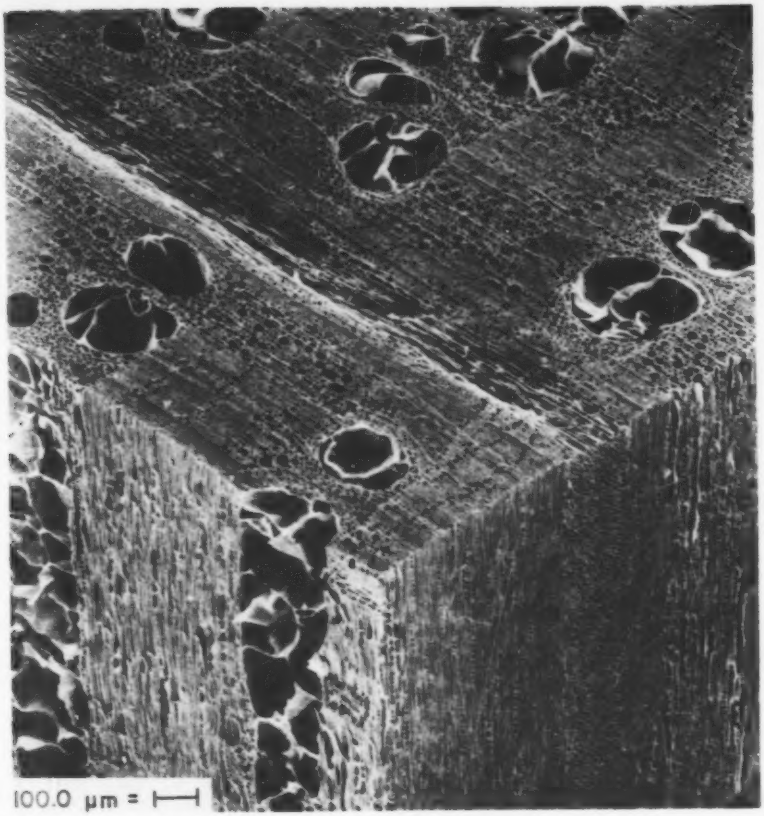

Figure 5-41.—White oak, the most important member of the white oak group (see fig. 5-33 for description). A broad ray is present. Note the abundance of tyloses in the earlywood vessels and the closely spaced, numerous, small, thin-walled, angular latewood pores; compare with southern red oak, fig. 5-39. (Scanning electron micrograph from W.A. Côté.)

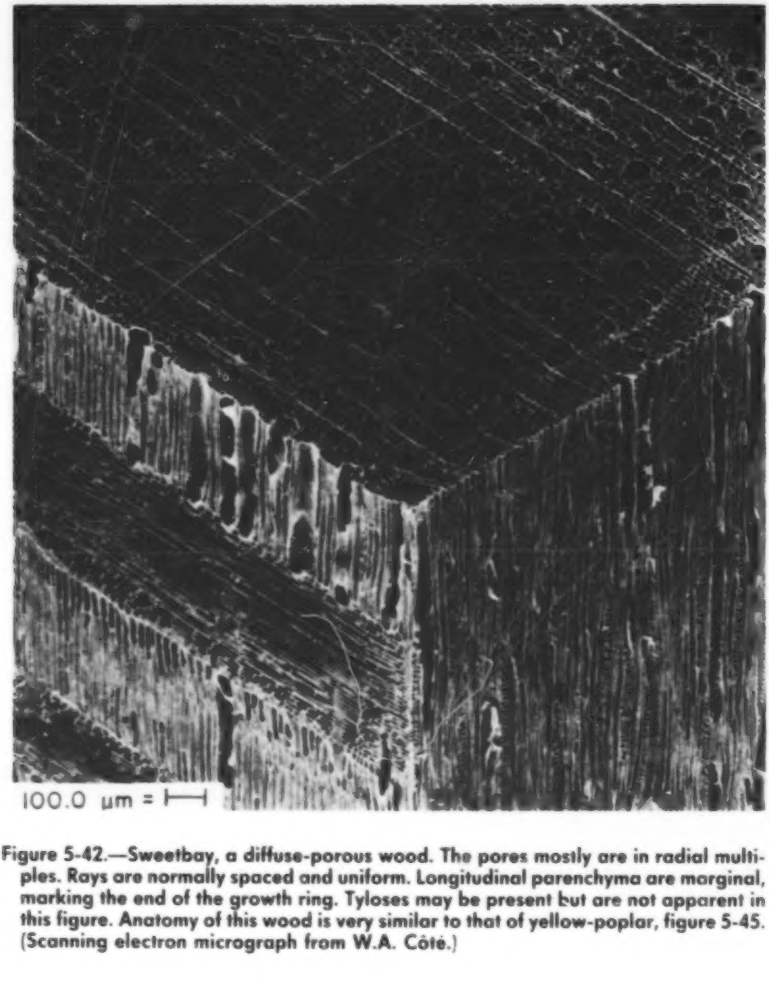

Figure 5-42.—Sweetbay, a diffuse-porous wood. The pores mostly are in radial multiples. Rays are normally spaced and uniform. Longitudinal parenchyma are marginal, marking the end of the growth ring. Tyloses may be present but are not apparent in this figure. Anatomy of this wood is very similar to that of yellow-poplar, figure 5-45. (Scanning electron micrograph from W.A. Côté.)

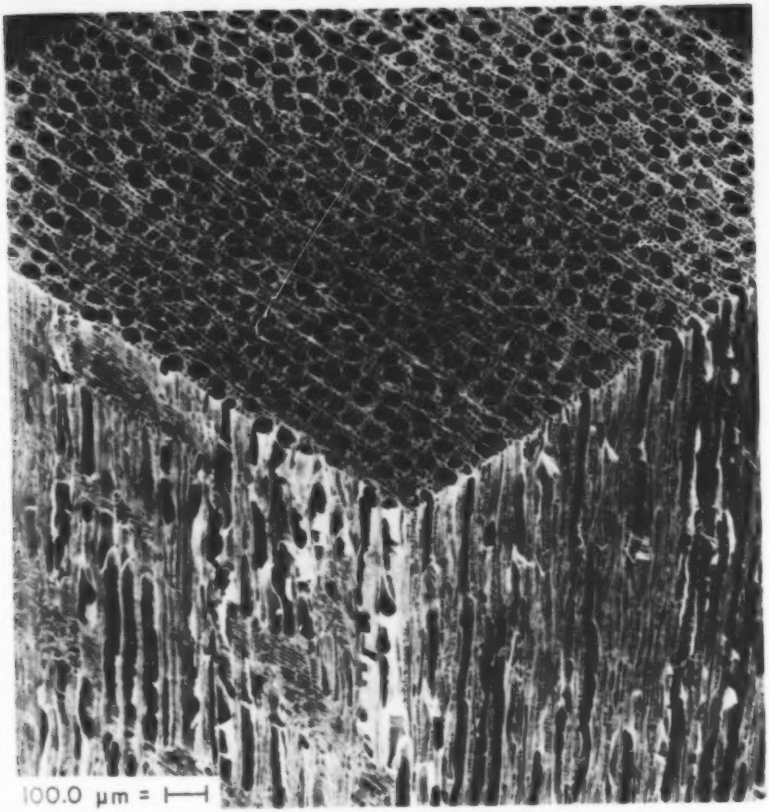

Figure 5-43.—Sweetgum, a diffuse-porous wood. The pores tend to be solitary, are very numerous, closely spaced and appear to occupy about one-half the transverse surface. Rays are very fine and closely spaced. Longitudinal parenchyma are sparse, strands of apotracheal-diffuse and paratracheal parenchyma occasionally present. Growth-ring boundaries are indistinct and are marked by a few rows of thick-walled and somewhat flattened fibers. (Scanning electron micrograph from W.A. Côté.)

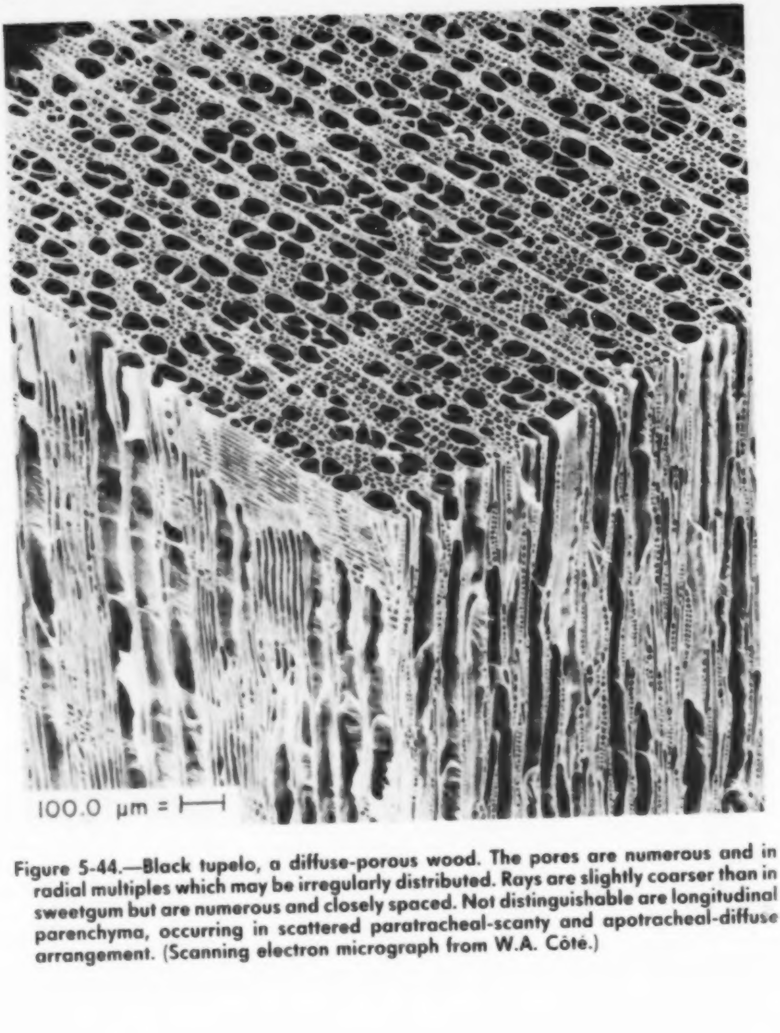

Figure 5-44.—Black tupelo, a diffuse-porous wood. The pores are numerous and in radial multiples which may be irregularly distributed. Rays are slightly coarser than in sweetgum but are numerous and closely spaced. Not distinguishable are longitudinal parenchyma, occurring in scattered paratracheal-scanty and apotracheal-diffuse arrangement. (Scanning electron micrograph from W.A. Côté.)

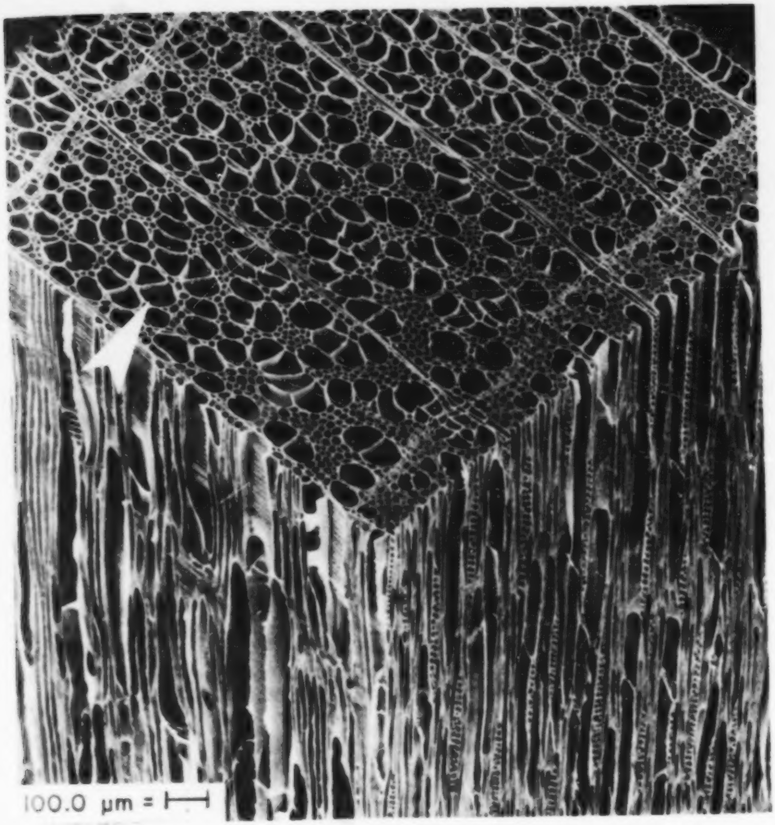

Figure 5-45.—Yellow-poplar, a diffuse-porous wood. The pores are numerous and in radial multiples that frequently are diagonal (arrow). Rays are normally spaced, much fewer than in sweetgum, and visible to the unaided eye. Longitudinal parenchyma are marginal, forming a continuous line of several rows. The pore distribution is variable, frequently being less numerous in outer latewood. Compare with sweetbay (fig. 5-42), a wood that is very similar. (Scanning electron micrograph from W.A. Côté.)

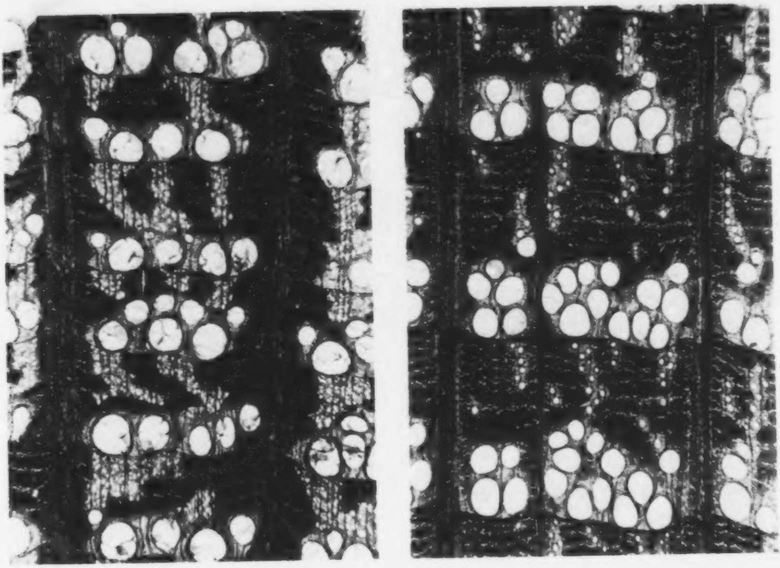

Figure 5-46.—Pore (vessel) arrangement in ring-porous oaks. (Left) White oak with numerous small latewood pores in dendritic arrangement. (Right) Northern red oak, with latewood pores also in dendritic arrangement, but more sparse and larger than those of white oak. Tyloses are present in white oak (left) and both woods have abundant paratracheal and apotracheal parenchyma. (Micrograph from W.A. Côté.) 15.5X

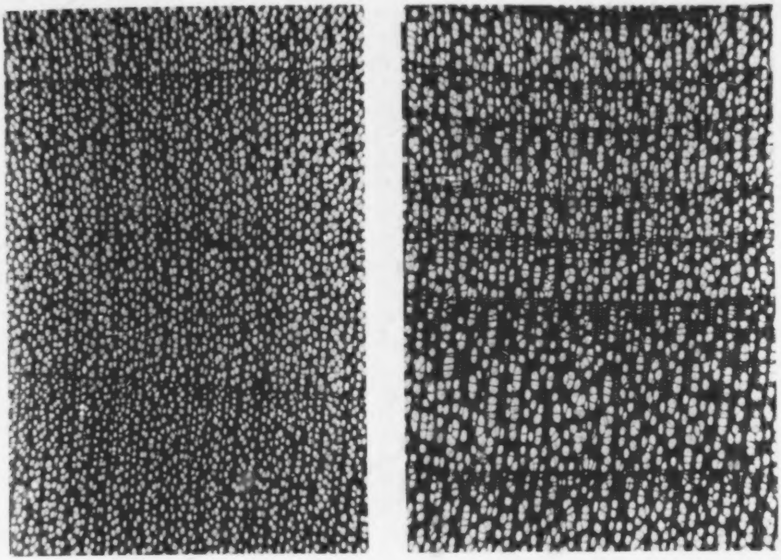

Figure 5-47.—Pore (vessel) arrangement in diffuse-porous hardwoods. (Left) Sweetgum; pores are uniformly distributed, closely spaced, and essentially solitary. (Right) Black tupelo, pores are in radial multiples and irregularly distributed. (Micrograph from W.A. Côté.) 15.5X

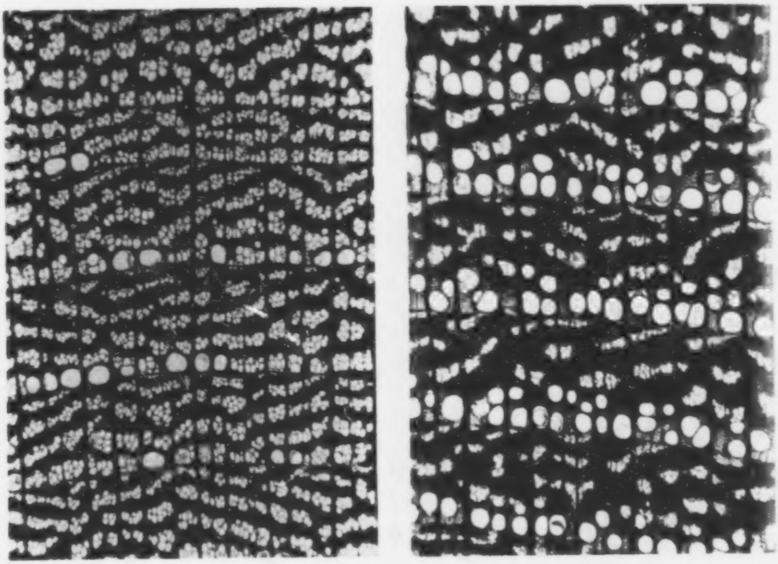

Figure 5-48.—Pore (vessel) arrangement in ring-porous elm and hackberry. (Left) American elm; the large earlywood pores are in a single, interrupted pattern. The smaller latewood pores are in typical ulmiform pattern (concentric, tangential, wavy bands). (Right) Hackberry; earlywood pores (large) are in several rows. The ulmiform pattern of the smaller latewood pores is less distinct and regular than in the elms. Rays of hackberry are more distinct than in elm. (Micrograph from W.A. Côté.) 15.5X

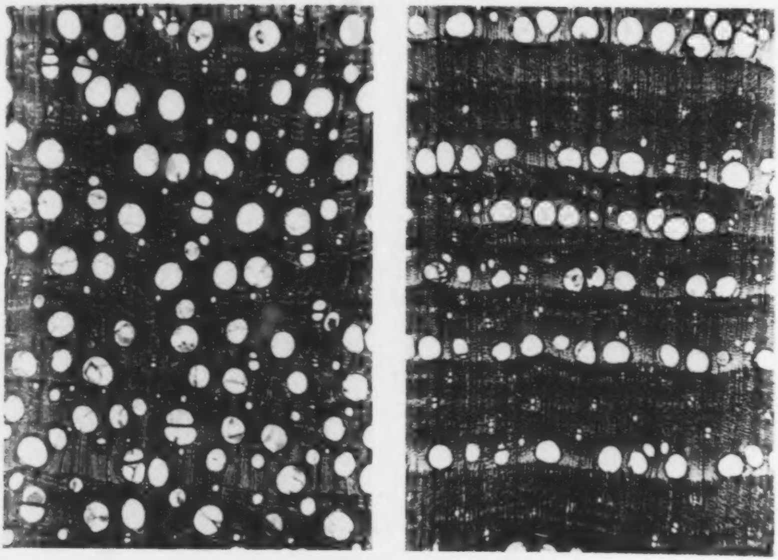

Figure 5-49.—Pore (vessel) arrangement in ring-porous hickory and ash. (Left) True hickory. (Right) White ash. Both woods have similar pore arrangement with latewood pores scattered and in radial multiples. However, true hickory has abundant apotracheal-banded parenchyma in the latewood, while the parenchyma in white ash is paratracheal and paratracheal-confluent. (Micrograph from W.A. Côté.) 15.5X

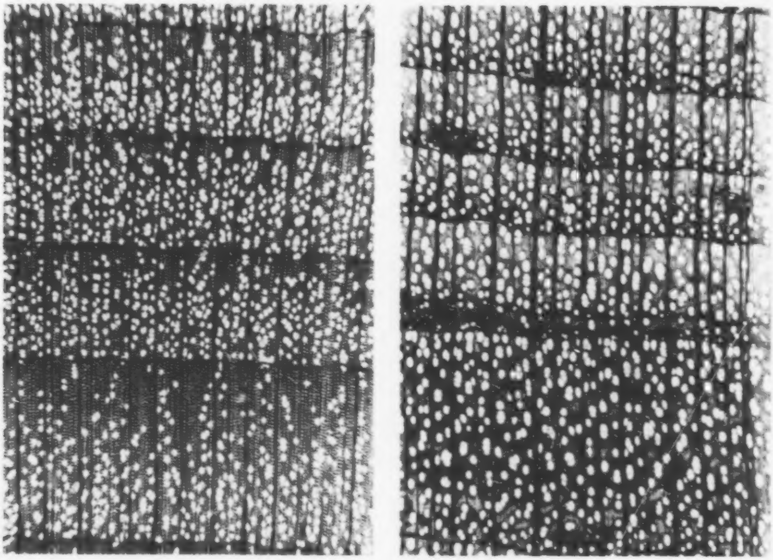

Figure 5-50.—Pore (vessel) arrangement in diffuse-porous sweetbay and red maple. (Left) Sweetbay; pores are in radial multiples and are less numerous in outer latewood. (Right) Red maple; pores are both solitary and in radial multiples and are uniformly distributed. The dark, irregular areas are wound tissue resulting from insect attack of the cambial layer (pith flecks). (Micrographs from W.A. Côté.) 15.5X

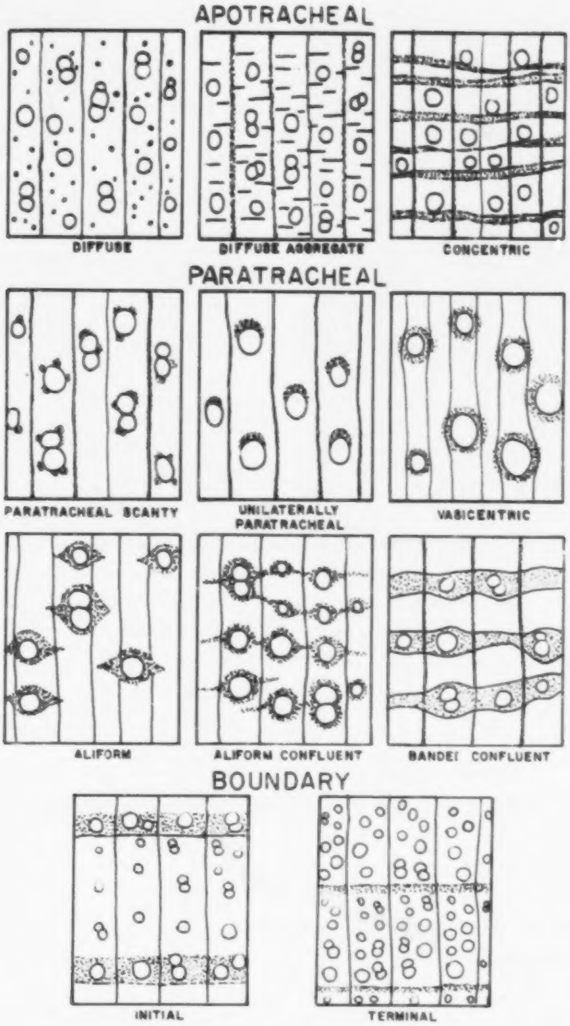
APOTRACHEAL
DIFFUSE
DIFFUSE AGGREGATE
CONCENTRIC
PARATRACHEAL
PARATRACHEAL SCANTY
UNILATERALLY PARATRACHEAL
VASICENTRIC
ALIFORM
ALIFORM CONFLUENT
BANDED CONFLUENT
BOUNDARY
INITIAL
TERMINAL

Figure 5-51.—Common longitudinal parenchyma arrangements in hardwoods. Terminology varies among authors and this drawing should be used only as a guide. *Boundary* parenchyma is usually (recent literature) referred to as *marginal*. The parenchyma is shown as dotted areas except in top left (isolated dots) and top center (horizontal lines). (Drawing adapted from Jane, F.W. 1970. The structure of wood. With permission of A & C Black (Publishers) Ltd.)

5-3 CELL COMPOSITION OF HARDWOODS

Hardwoods are more complex than softwoods, containing more different types of cells. Not all hardwoods contain the same types nor are they distributed in the same proportions. Species of hardwoods growing among southern pines may contain the following cell types:

Longitudinal Cells

- Vessel elements
- Fibers
  - Fiber tracheids
  - Libriform fibers
- Tracheids
  - Vasicentric tracheids
  - Vascular tracheids
- Axial parenchyma
  - Strand parenchyma
  - Fusiform parenchyma
  - Epithelial parenchyma

Horizontal Cells

- Ray parenchyma
  - Procumbent cells
  - Upright cells

Vessel elements, fibers of one or both types, axial parenchyma and ray parenchyma occur in all hardwoods described in this text. Fusiform parenchyma occurs in the marginal parenchyma of red maple; vasicentric tracheids are found only in the oaks, vascular tracheids are restricted to the elms and hackberry, and epithelial cells are found in the longitudinal gum canals resulting from wounds in sweetgum. Procumbent ray parenchyma are present in all these hardwoods; upright ray cells are found in several species as noted in the keys (sect. 5-11).

5-4 STRUCTURE OF LONGITUDINAL ELEMENTS

VESSEL ELEMENTS

Vessel elements in longitudinal series comprise the segmented structure termed a **vessel** (k, k^1, and k^2 in fig. 5-21), which in transverse section exposes a pore (fig. 5-22). Although the direction of alignment of a vessel is vertical, it may deviate as well as divide during its development. Several investigators have noted that vessels may be continuous from the base to the top of the tree.

Vessel elements are relatively short and large in diameter compared to the fibers. Lengths may range from less than .30 mm to more than 1.30 mm and tangential diameters from 50 μm to 300 μm or more (Panshin and deZeeuw 1980). Unique to vessel elements are the **perforations** at each end which allow, in some species, unimpeded flow of liquids through the vessel. Most woods have **simple** vessel element perforations, a few are **scalariform** (fig. 5-52). See also figures 8-33D and 8-34AB for scalariform perforations in sweetgum, and figure 8-35CD for scalariform perforations in black tupelo.

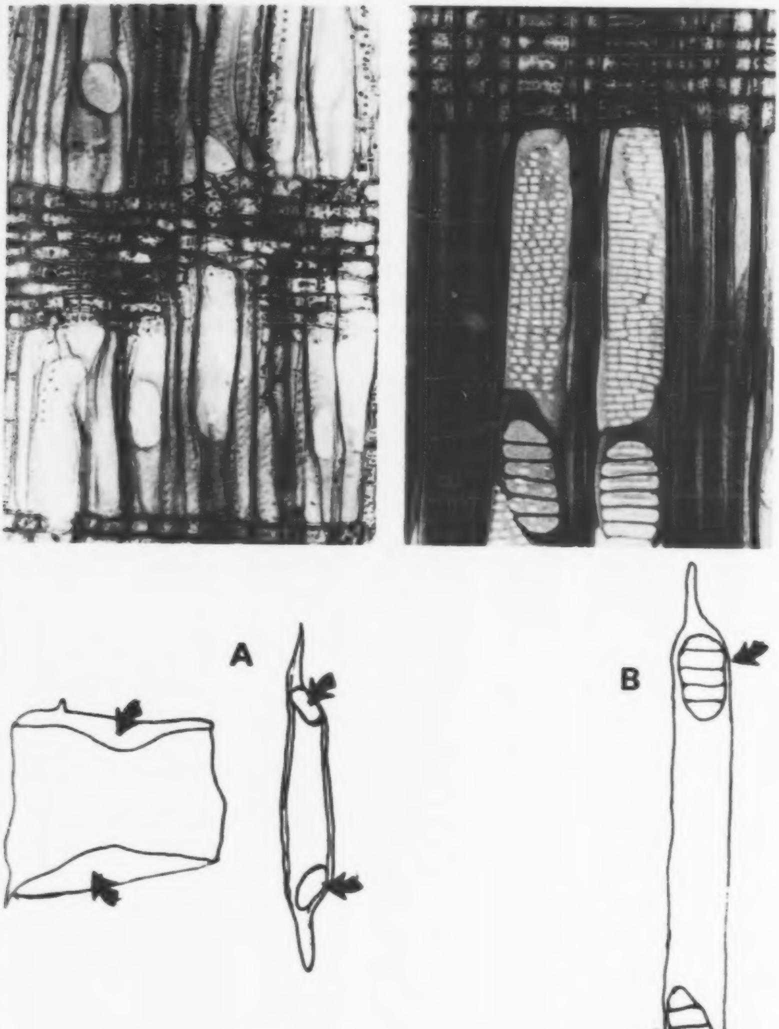

Figure 5-52.—Vessel element perforations. (Top left) Cherrybark oak with simple vessel element perforations. (Top right) Sweetbay with scalariform vessel element perforations. (Micrographs from W.A. Côté.) 15.5X

(Bottom) Vessel element perforations (arrows). Sketch (A) shows isolated red oak vessel elements with simple perforations; on the left is an earlywood vessel element, and on the right a latewood vessel element with thick walls. Sketch (B) shows a yellow-poplar vessel element with scalariform perforations. (Drawings from H.A. Core.) 90X

FIBERS

The term **fiber** is collective and normally includes all of the long cells wit relatively thick walls and tapering ends (Panshin and deZeeuw 1980). In anatomical studies, the term is restricted to **fiber tracheids** (b-b^4 in surface A and in surface C of fig. 5-21) and **libriform fibers;** these two elements largel determine the strength, hardness, weight and chemical composition of hardwoods. Fiber tracheids and libriform fibers overlap in characteristics and onl the extremes, anatomically, can be recognized. The major difference is th presence of bordered pits in fiber tracheids (fig. 5-53AB) and simple pitting i libriform fibers. Fibers, along with vessel elements, and vascular and vasicentri tracheids die soon after differentiation from the cambium.

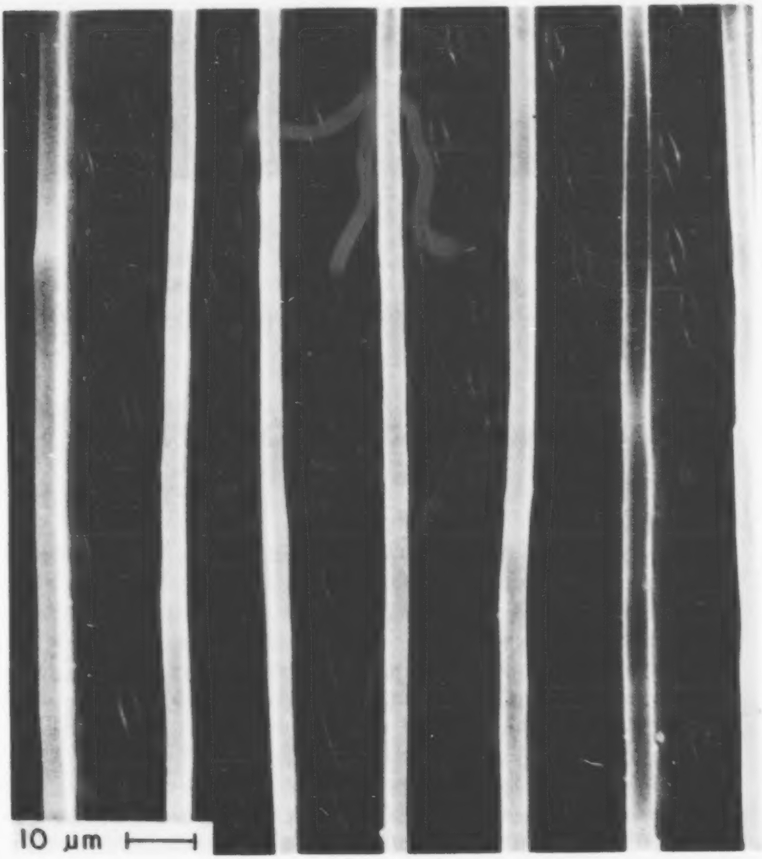

Figure 5-53A.—Fiber tracheids of sweetbay in radial view. Bordered-pit apertures are slitlike and aligned parallel to fibrils in the S2 layer of the secondary wall. The fibri angle appears to be about 10 degrees. (Scanning electron charcoal micrograph from W.A. Côté.)

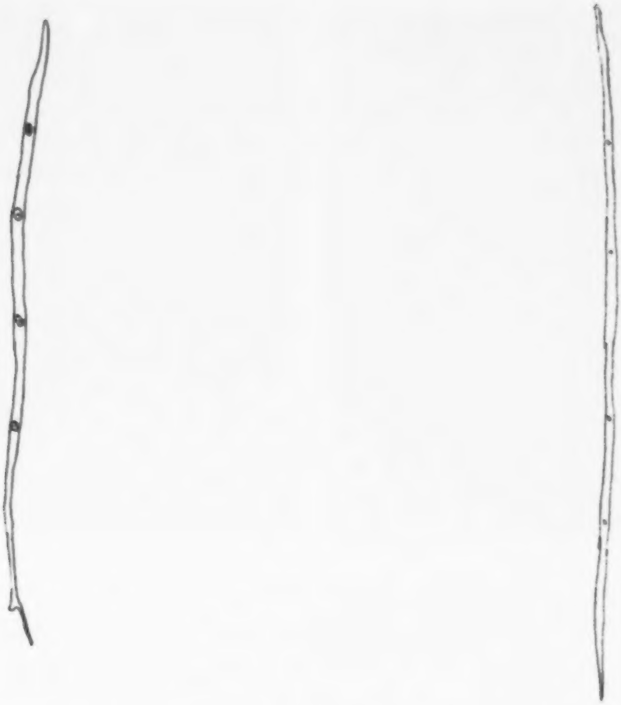

Figure 5-53B.—Hardwood fibers (typical). (Left) Sketch of fiber tracheid of sweetgum, X90. Pits are bordered and relatively conspicuous. (Right) Sketch of libriform fiber of American elm, X180. Pits are minute and either simple or inconspicuously bordered. The two types intergrade and both types may be present in the same wood. Separation is difficult except in the most typical instances. (Drawing from H.A. Core.)

TRACHEIDS

Vasicentric tracheids appear to be transitional in nature and, among the hardwoods described in this text, occur only in the oaks (Panshin and deZeeuw 1980). They are shorter than fibers, larger in diameter, somewhat contorted and have numerous bordered pits along with **crassulae** (thickenings of the middle lamella and cell wall). They occur in close association with the vessel elements (figs. 5-54 left and 5-55 left). **Vascular tracheids** also appear to be transitional elements and are found only in the elms and hackberry (figs. 5-54 right and 5-55 right). They appear identical to latewood vessel elements except that the end walls are pitted rather than perforated.

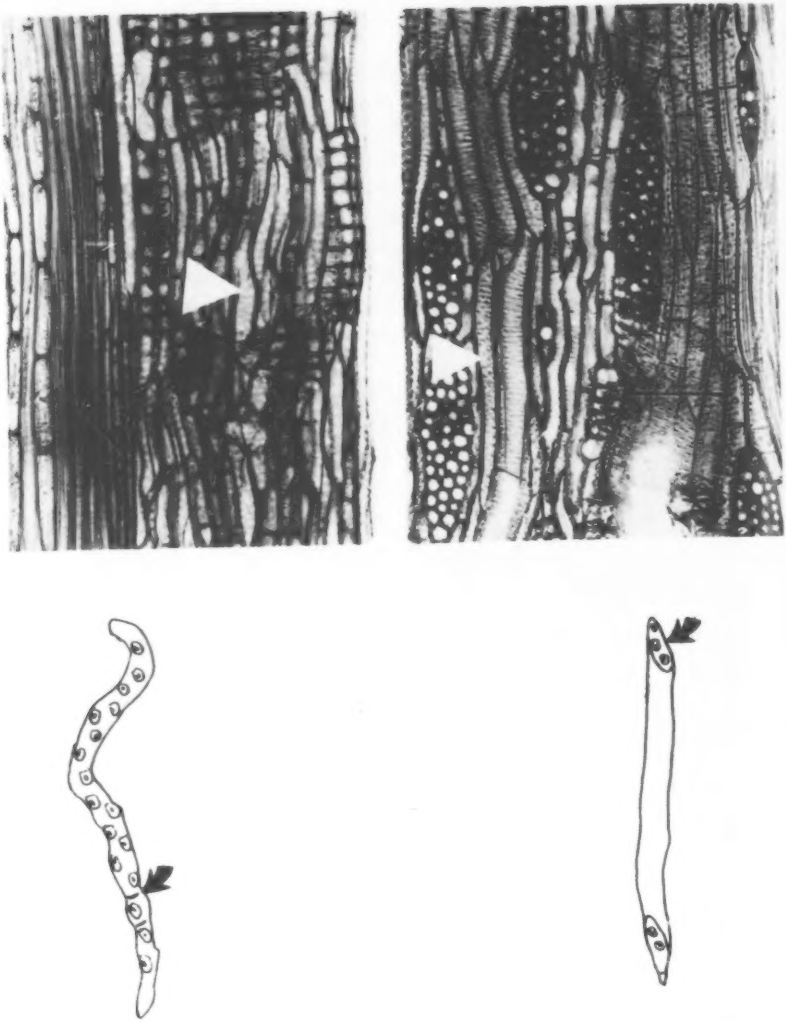

Figure 5-54.—Hardwood tracheids. (Top left) Radial view of *vasicentric tracheids* in cherrybark oak (arrow). Strands of longitudinal axial parenchyma may be seen at left border. (Top right) Tangential view of *vascular tracheids* in winged elm (arrow). The vascular tracheids are intermingled with latewood vessel elements and are difficult to identify in wood sections. (Micrographs from W.A. Côté.) 157X (Bottom left) Sketch of isolated vasicentric tracheid of red oak in radial view, X90. Element is irregular in shape and intertracheary pitting is abundant. *Crassulae* (zones of darker wall tissue) occasionally are present (arrow). (Bottom right) Sketch of isolated vascular tracheid of hackberry in radial view, X180. Element is similar to latewood vessel element in size, pitting and sculpturing but end walls (arrow) contiguous to other cells in longitudinal series are pitted rather than perforate. (Drawings from H.A. Core.)

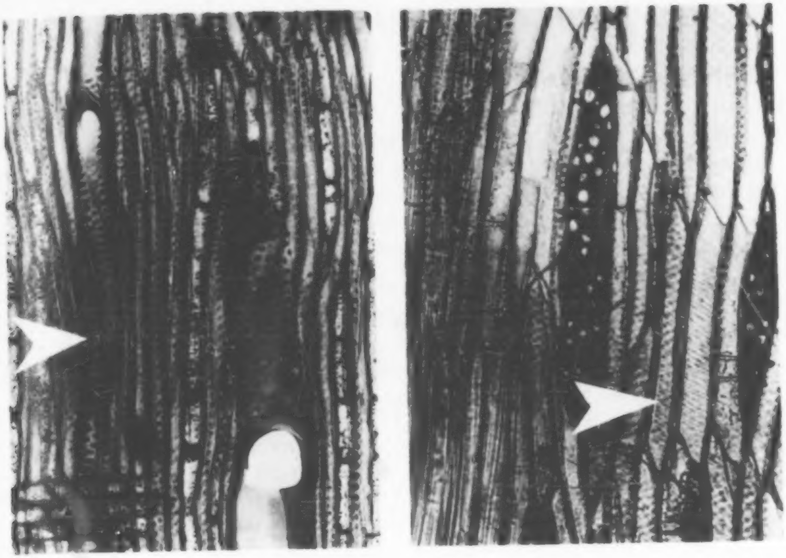

Figure 5-55.—Hardwood tracheids. (Left) Radial view of *vasicentric tracheids* in blackjack oak (arrow). Several strands of longitudinal parenchyma and vessel elements with simple perforations are present. (Right) Tangential view of *vascular tracheids* in American elm (arrow). The tracheids are intermingled with latewood vessel elements. (Micrographs from W.A. Côté.) 157X

LONGITUDINAL PARENCHYMA

Longitudinal axial parenchyma cells (CC^2C^3 in surface A of fig. 5-21 and fig. 5-55 left) usually are found in strands of up to 15-20 cells, each strand arising from a single living cell produced within the cambial layer. Parenchyma cells are characterized by having simple pits, short lengths, and horizontal end walls. Parenchyma cells serve as storage reservoirs and remain active (alive) in the sapwood of the tree.

Epithelial cells are secreting cells surrounding a cavity. Among pine-site hardwoods they occur only in sweetgum, where they may arise as a result of wounding.

5-5 STRUCTURE OF HORIZONTAL ELEMENTS

RAY PARENCHYMA CELLS

Horizontal tissue (ray cells) in hardwoods that grow among southern pines is comprised of **ray parenchyma.** These cells occur in several shapes and arrangements (fig. 5-56). Most rays are principally comprised of **procumbent** cells with long axis oriented horizontally. Frequently, the margins of some rays will contain one or more rows of cells with the long axis vertical or **upright.** Rays in which all the cells are procumbent (occasionally all upright) are termed **homocellular;** those with both shapes present in the same ray are called **heterocellular.** Heterocellular rays are found in sweetgum, black tupelo, yellow-poplar, sweetbay and hackberry, while homocellular rays are typical of the oaks, red maple, the ashes, hickory and to a lesser extent, elm. (See figs. 5-57 through 5-61 for examples.)

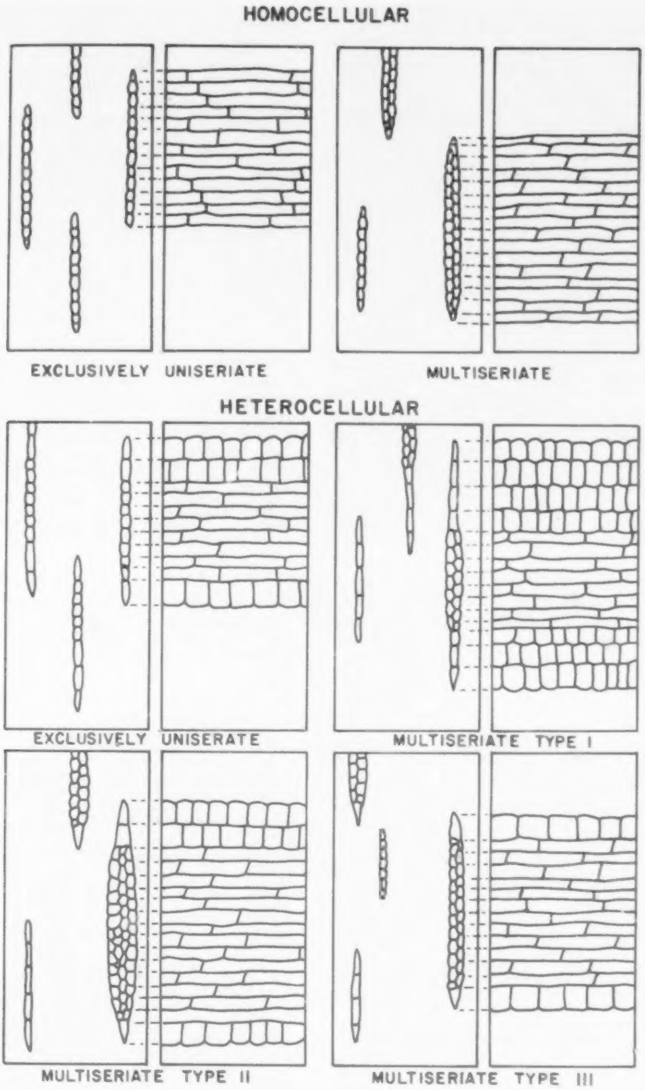
HOMOCELLULAR
EXCLUSIVELY UNISERIATE
MULTISERIATE
HETEROCELLULAR
EXCLUSIVELY UNISERATE
MULTISERIATE TYPE I
MULTISERIATE TYPE II
MULTISERIATE TYPE III

Figure 5-56.—Common types of hardwood rays. Tangential views are at left, and radial views at right. Heterocellular rays include upright cells at top and bottom, and *procumbent* cells between. Homocellular rays usually have only procumbent cells. Not shown are homocellular rays composed entirely of upright cells (rare), or broad rays up to 50+ cells wide characteristic of the oaks (figs. 5-22 and 5-31 through 5-41). (Drawing adapted from Jane, F.W. 1970. The structure of wood. With permission of A & C Black (Publishers) Ltd.)

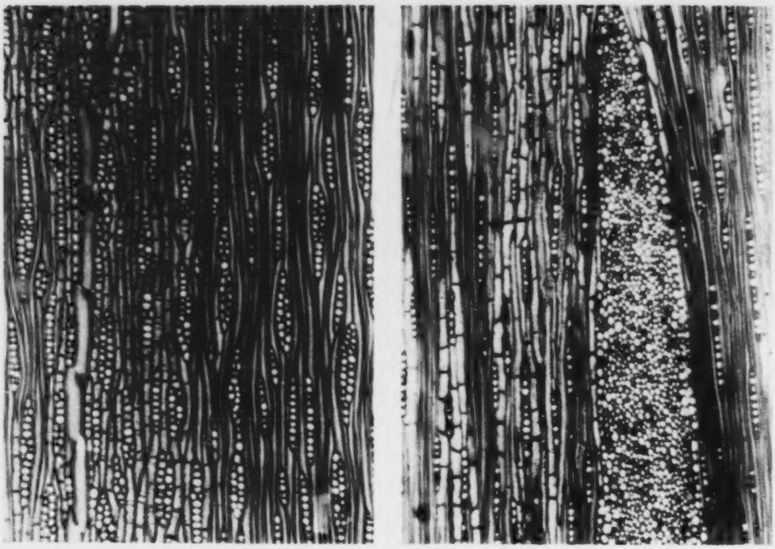

Figure 5-57.—Homocellular rays in green ash and black oak; tangential views. Green ash (left) has rays one-to-two seriate. Black oak (right) has rays that are either very broad (multi-seriate) or uniseriate. (Micrographs from W.A. Côté.) 60X

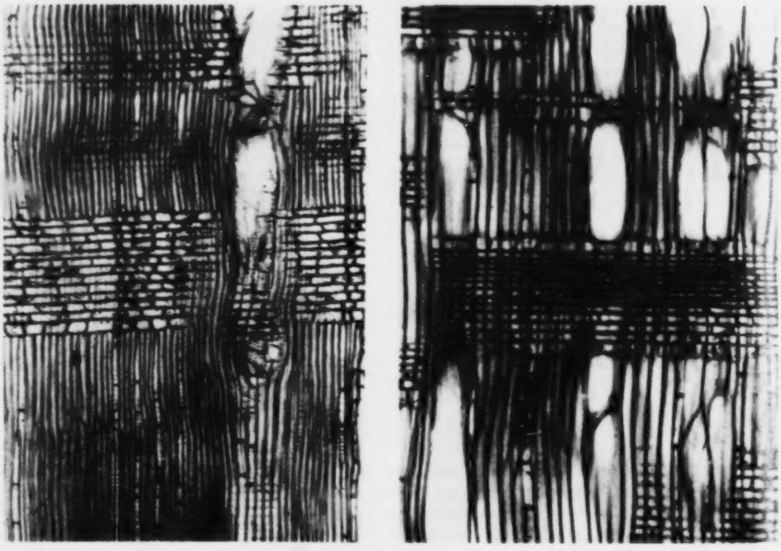

Figure 5-58.—Radial views of *homocellular* rays in true hickory (left), and *heterocellular* rays in sweetgum (right). (Micrographs from W.A. Côté.) 60X

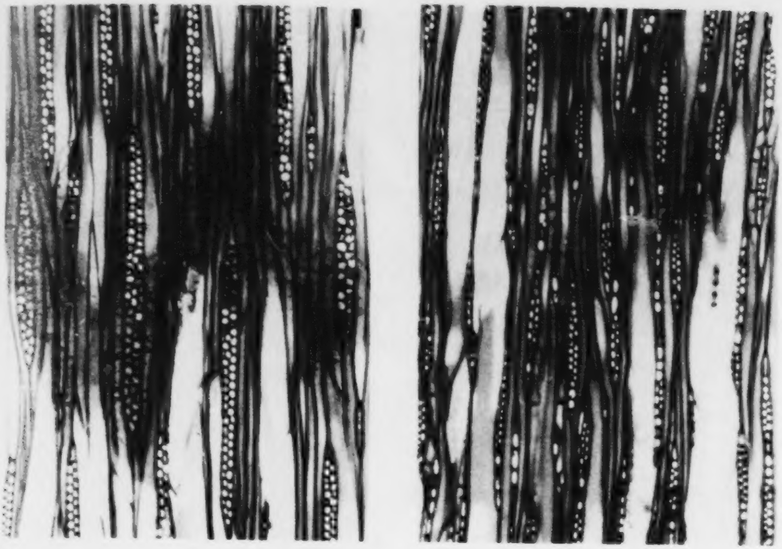

Figure 5-59.—Tangential view of heterocellular rays in yellow-poplar (left) and black tupelo (right). Upright cells, visible at upper and lower ray edges, may be in several rows in black tupelo (multiseriate Type I of fig. 5-56), but are usually in single rows in yellow-poplar (multiseriate Type III of fig. 5-56). (Micrographs from W.A. Côté.) 60X

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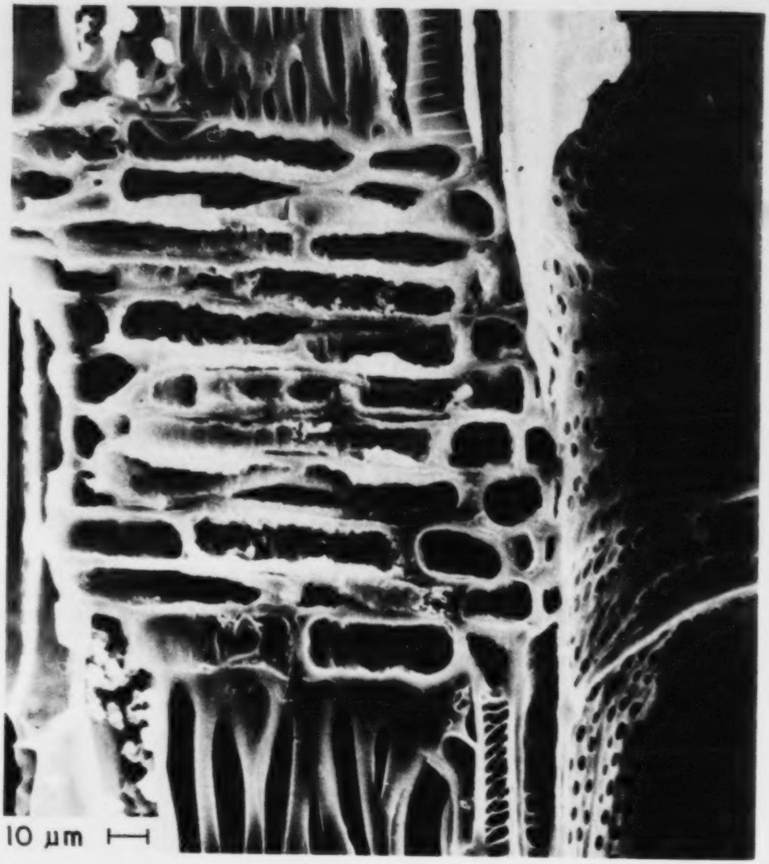

Figure 5-60.—Homocellular ray of American elm in radial view; all cells procumbent. Ray-vessel pitting visible at right of ray. (Scanning electron micrograph from W.A. Côté.)

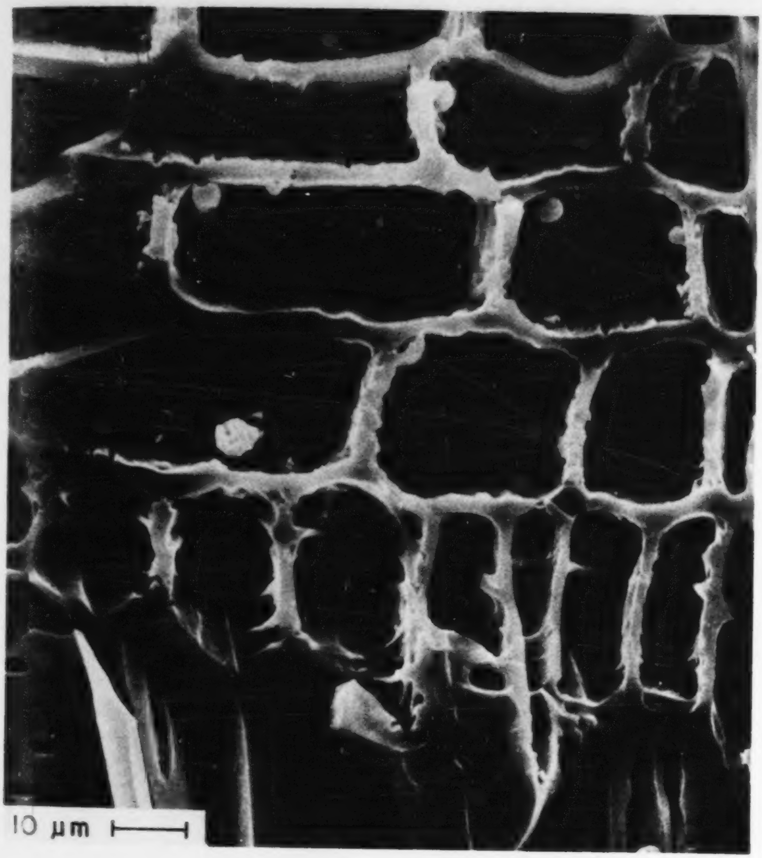

Figure 5-61.—Heterocellular ray in radial view of yellow-poplar. Procumbent cells of the ray are bordered at lower edge by a single row of upright cells. (Scanning electron charcoal micrograph from W.A. Côté.)

5-6 PITTING AND SCULPTURING OF CELL WALLS

PITS

Pits are gaps left in the secondary wall of the cell, subtended by a modified primary wall which is the **pit membrane** (figs. 5-62 and 8-31 through 8-35). Pits nearly always have **complementary** pits in the opposing cell wall, the two comprising a **pit-pair.** Pits may be modified in several ways: the cavity may be constricted at the cell lumen to give a **chamber** and **aperture,** or the wall layer beyond the chamber may form a **canal** with an **inner** (lumen side) and **outer** (chamber side) aperture. Pits are **bordered** if they have chambers and are **simple** if a uniform cavity is present. The type of pit formed is not as consistent with the nature of the cell in hardwoods as it is in softwoods and thickened pit membranes (tori) are not present. The shape, type, and arrangement of pitting in vessel elements and rays are useful in species identification.

Intervessel pitting arrangement occurs in three patterns: **alternate,** the most common (fig. 5-63); **opposite;** and **scalariform** (fig. 5-64). The **pit outline** of intervessel pitting may be angular and crowded, rounded, rectangular or scalariform. Simple pits, when they occur as ray-to-vessel pits, may be round, oval, or horizontally elongated. (Figs. 5-63 through 5-68 give examples of intervessel pitting arrangement.) Figures 8-31, 8-32, and 8-33 provide electron micrographs of cross-sectional and surface views of intervessel pits. Pine-site hardwoods have the following intervessel pitting arrangements:

Alternate: Pit-outlines rounded, oval or angular	Opposite: Pit outlines rectangular	Scalariform: Pit outlines linear or rectangular
Ash sp.	Sweetgum (usually)	Sweetbay
Elm sp.	Tupelo, black	Sweetgum (occasionally)
Hackberry	Yellow-poplar	
Hickory sp.		
Maple, red		
Oak sp. (extremely rare)		

Intervessel pitting is rare in the oaks and infrequent in sweetgum, species in which vessels are distributed in a solitary pattern within growth rings. Alternate pitting when not crowded has pit outlines rounded to oval; if crowded, the outlines tend to be polygonal (angular).

Ray-to-vessel pitting usually is compared with intervessel pitting, being similar or dissimilar. When it is unlike the intervessel pitting, it may be simple and rounded, oval or elongated.

Fiber-to-fiber, fiber-to-vessel element, and **fiber-to-ray cell** pits are recognizable in some species, but are only of minor importance in identification. Figures 8-33C, 8-34CD, and 8-35AB show cross sections of interfiber pit pairs in sweetgum sapwood and heartwood.

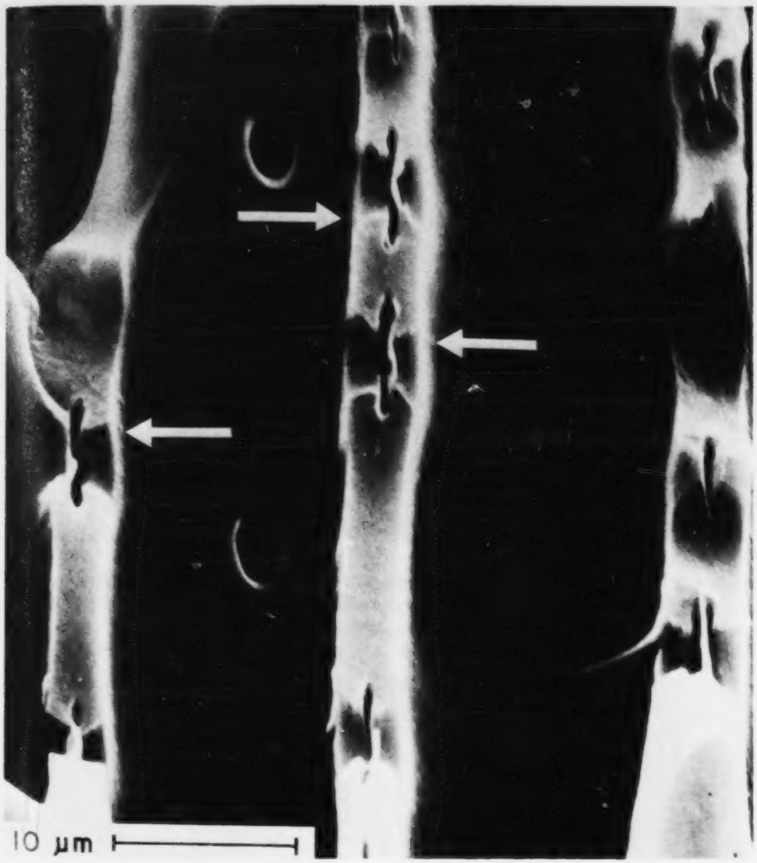

Figure 5-62.—Bordered pit-pairs in radial sectional view between fiber tracheids of sweetgum. The fiber tracheid walls are thick and pit canals with inner and outer apertures are present. (Scanning electron charcoal micrograph from W.A. Côté.)

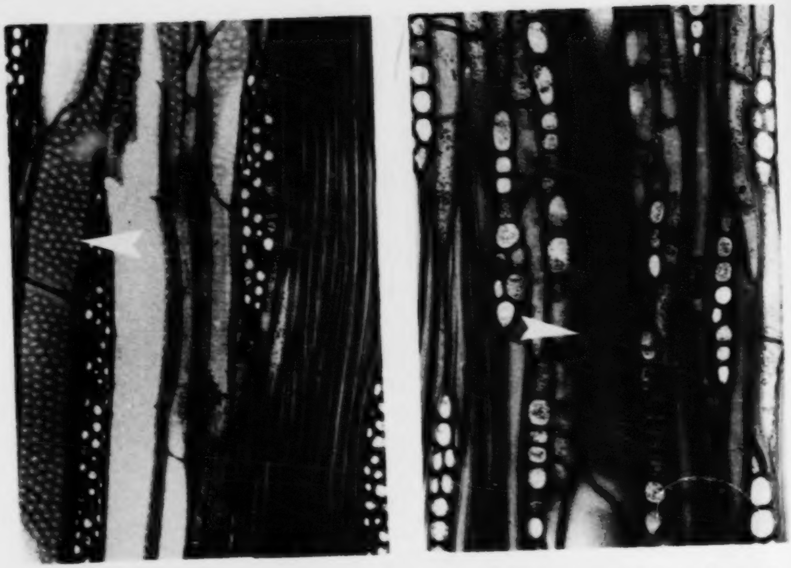

Figure 5-63.—Alternate intervessel pitting arrangement in tangential view (arrows). (Left) American elm; pits are angular in outline and crowded. (Right) White ash; pits are rounded in outline. (Micrographs from W.A. Côté.) 157X

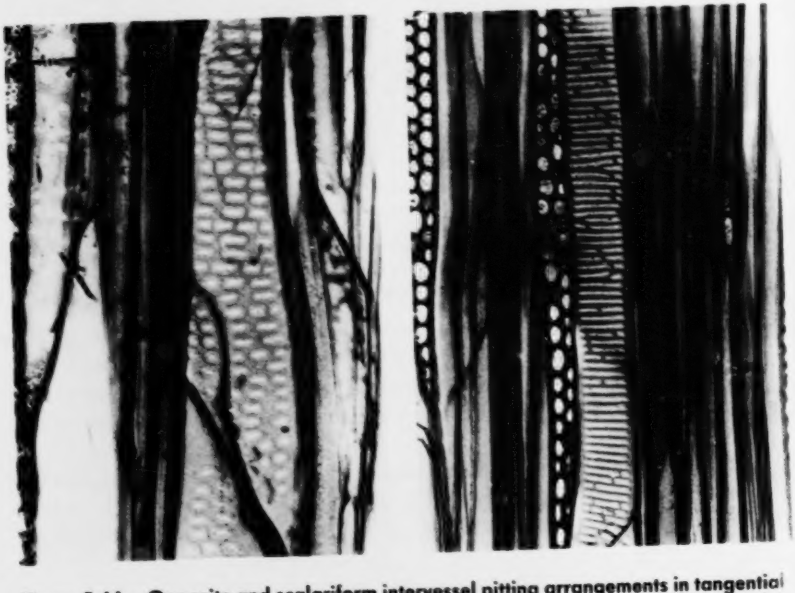

Figure 5-64.—Opposite and scalariform intervessel pitting arrangements in tangential view. (Left) Opposite pitting in yellow-poplar; pits are rectangular in outline. (Right) Scalariform pitting in sweetbay; pits are horizontally elongated (linear) in outline. (Micrographs from W.A. Côté.) 152X

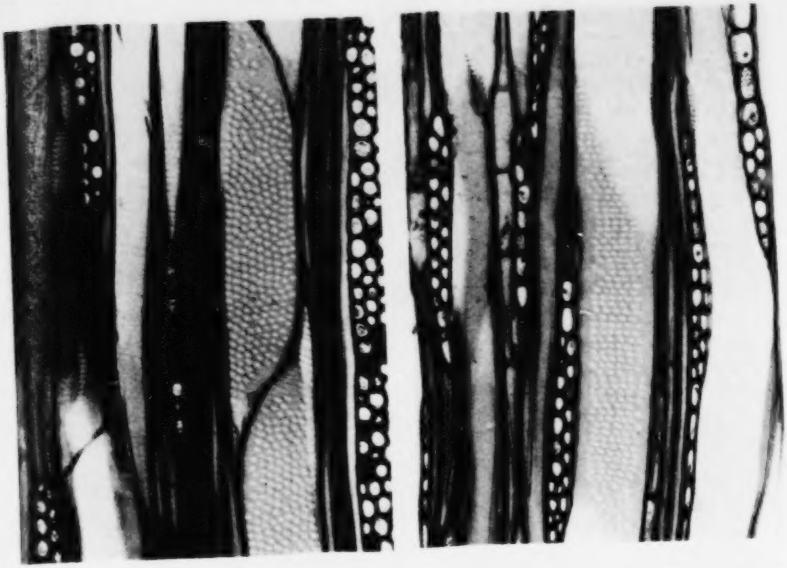

Figure 5-65.—Alternate and opposite intervessel pitting arrangements in tangential view. (Left) Alternate pits in red maple are angular in outline and crowded. (Right) Opposite pits in black tupelo are nearly square in outline with up to 6 pits per row; see also figure 5-66. (Micrographs from W.A. Côté.) 161X

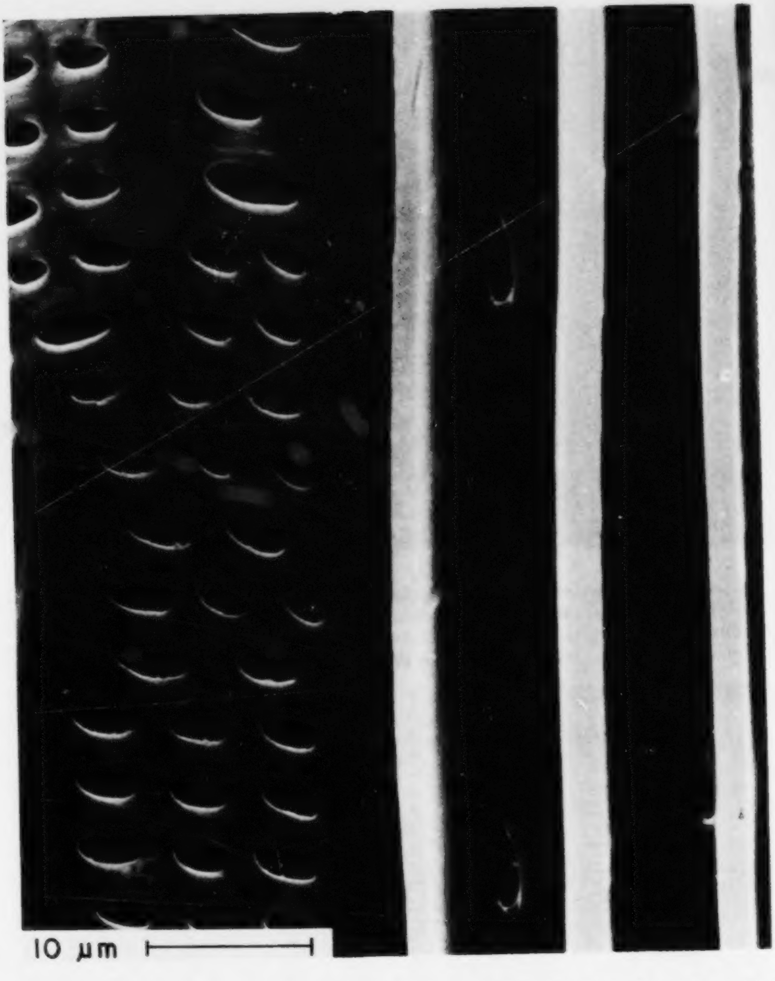

Figure 5-66.—(Left) Opposite intervessel pitting arrangement in black tupelo, radial view; apertures to pits are large and oval, but outlines of pit chambers are not visible. (Right side of same section) Bordered pits in fiber tracheids. (Scanning electron charcoal micrograph from W.A. Côté.)

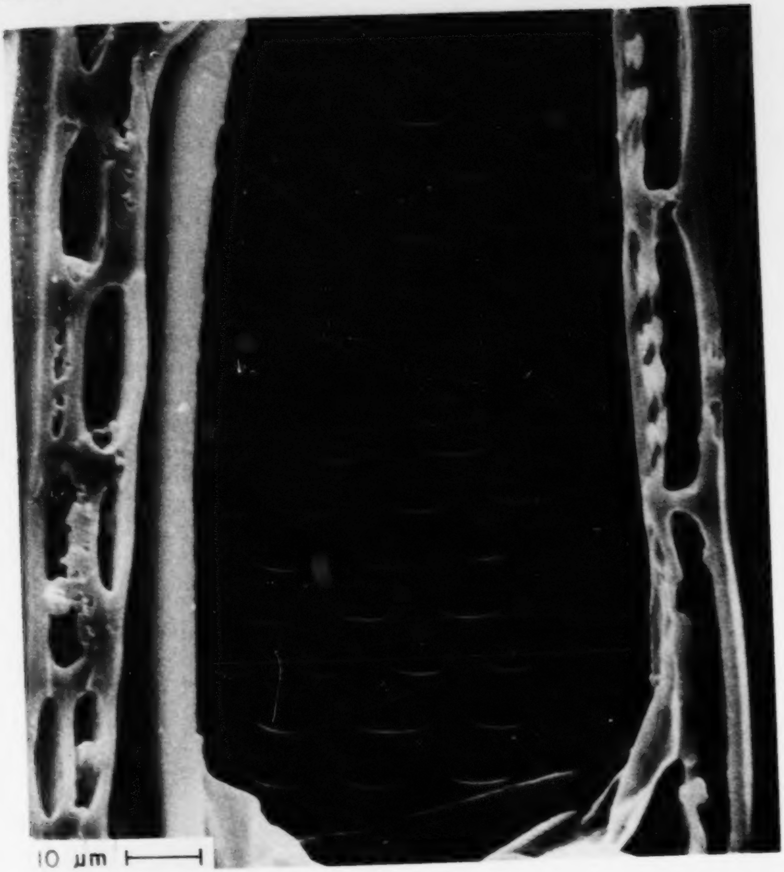

Figure 5-67.—Opposite intervessel pitting in yellow-poplar, tangential view. Apertures to pits are narrow ovals; outlines of pit chambers not visible. Ray cells are visible on both sides of the vessel. (Scanning electron charcoal micrograph from W.A. Côté.)

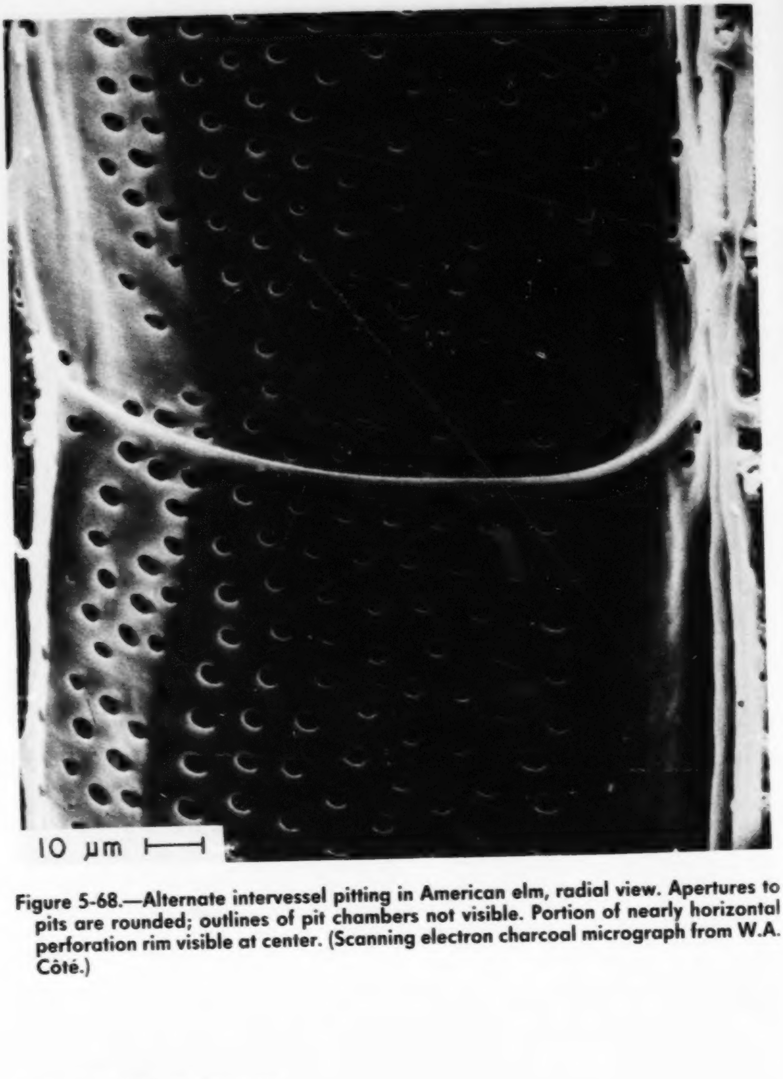

Figure 5-68.—Alternate intervessel pitting in American elm, radial view. Apertures to pits are rounded; outlines of pit chambers not visible. Portion of nearly horizontal perforation rim visible at center. (Scanning electron charcoal micrograph from W.A. Côté.)

HELICAL THICKENING

Helical (spiral) thickenings (figs. 5-69 and 5-70) are localized thickenings of the secondary wall lining the cell lumen and forming part of the S3 or inner layer of the secondary wall. Among pine-site hardwoods, these thickenings are restricted to the vessel elements of red maple and sweetbay, the latewood vessel elements and vascular tracheids of elm and hackberry and the extreme vessel tips of sweetgum and black tupelo. The significance of this form of sculpturing is unknown.

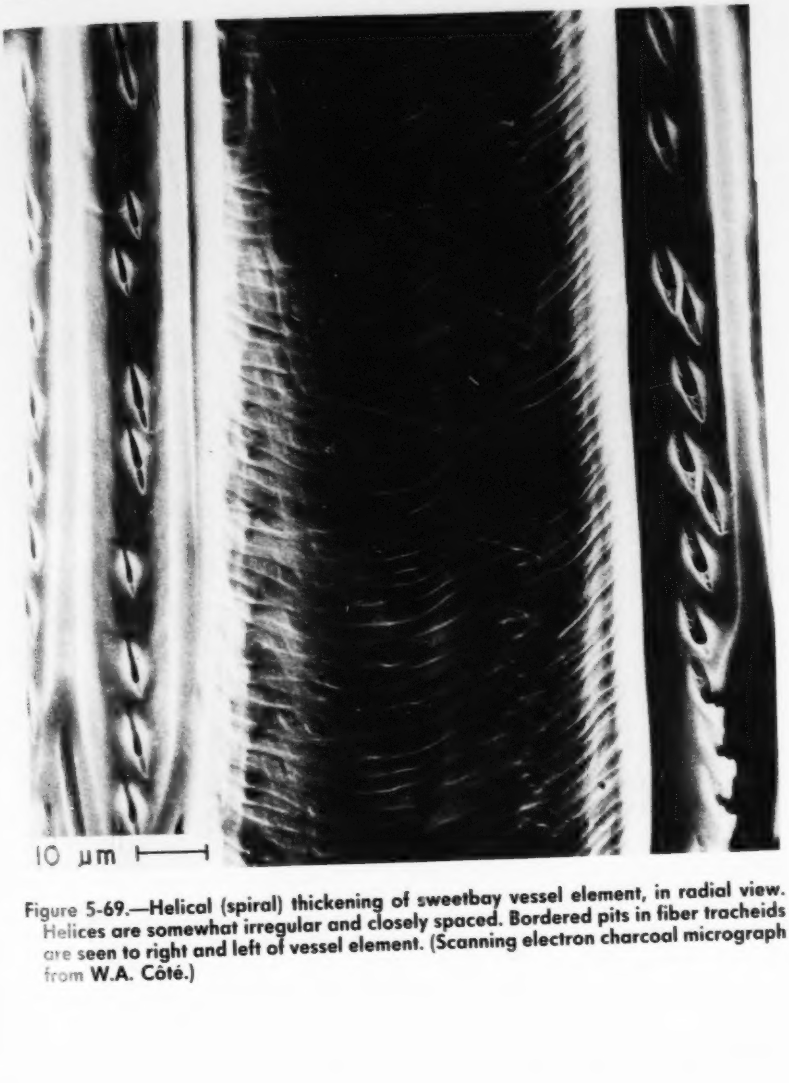

Figure 5-69.—Helical (spiral) thickening of sweetbay vessel element, in radial view. Helices are somewhat irregular and closely spaced. Bordered pits in fiber tracheids are seen to right and left of vessel element. (Scanning electron charcoal micrograph from W.A. Côté.)

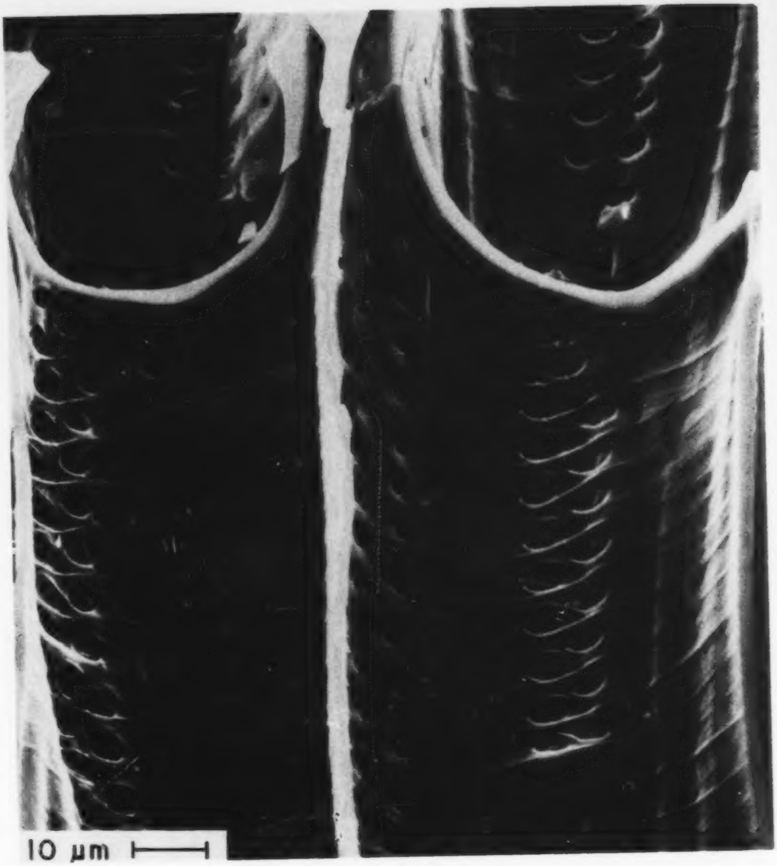

Figure 5-70.—Helical (spiral) thickening of American elm vessel elements in radial view. Portions of two simple perforation rims are visible in upper third of micrograph. (Scanning electron charcoal micrograph from W.A. Côté.)

EXTRANEOUS MATERIALS

Under this heading are included the numerous and various organic compound and minerals found in cells and cell walls which are non-essential either to th structure or development of the cell. The organic compounds, often referred t as **extractives,** include polyphenols and oleoresins. Less common are gums, tropolones, fats, fatty acids, waxes, and volatile hydrocarbons (see sect. 6-6). Most of these materials are deposited or formed in the cell at the time o heartwood formation (see sect. 5-1); starch, however, is formed almost exclusively in living cells as a reserve food. Oils, occasionally, may be stored in living cells for the same purpose (Jane 1970). Extractives may give a characteristic color to the heartwood. Others impart insect and decay resistance and occasionally alter the physical and mechanical properties of a wood. Some compounds occur in quantities great enough to be of commercial importance. None of the species discussed in this chapter contain extractives in sufficient quantity to be of commercial importance, although the extractives (or tyloses) in heartwood of the chestnut, post, and white oaks impart special qualities (decay resistance and low permeability) to these woods.

The mineral content of wood usually is less than 0.5 percent of ovendry weight (sect. 6-7, table 6-18). The most commonly recognized compounds are in the form of rhomboidal or styloidal crystals. The alkaline earths, especially calcium, account for most of the mineral material in wood (tables 6-19 and 6-26).

TYLOSES

Tyloses are inclusions found in hardwoods almost exclusively in the vessels. These interior growths are formed by the extrusion and growth of protoplasm from adjacent parenchyma cells (usually ray parenchyma) into the vessel lumen forming saclike structures. This usually occurs during heartwood formation, but occasionally results from wounding, disease or stress. Tyloses usually are restricted to woods with large (10-15 μm) pit apertures between ray parenchyma and vessels (Panshin and deZeeuw 1980; Chattaway 1952). When the pit apertures are smaller, gums and resins commonly are deposited within the vessel. Among the woods described in this chapter, white oak has abundant tyloses (figs. 5-13 and 5-22) in the earlywood of the heartwood. Post oak and chestnut oak (both white oaks) also have tyloses, but somewhat fewer in number (figs. 5-10 bottom and 5-9 top). The red oaks have relatively few tyloses, but some are visible in blackjack oak and cherrybark oak (figs. 5-8 top, 5-31, and 5-32). All of the other species except red maple show tyloses in varying amounts. Red maple (fig. 5-7 top) normally is devoid of tyloses but its vessels frequently contain gum. Further information on tyloses may be obtained from Gerry (1914), Kórán and Côté (1964), Meyer (1967), Murmanis (1975, 1976), Panshin and de Zeeuw (1980), and Sachs et al. (1970).

5-7 REACTION WOOD

Reaction wood in hardwoods is called **tension wood,** defined by the International Association of Wood Anatomists, Committee on Nomenlature (1964) as, "reaction wood formed typically on the upper sides of branches and leaning or crooked stems of dicotyledonous trees and characterized anatomically by lack of cell wall lignification and often by presence of an internal **gelatinous layer** in the fibers." Because tension wood with abundant gelatinous fibers is most easily recognized, it has received most attention by investigators, but lack of cell wall lignification is a better criterion for tension wood.

Gelatinous fibers have a **G layer** (fig. 5-71), a loosely attached, irregular, internal wall of nearly pure crystalline cellulose with a fibrillar angle essentially parallel to the longitudinal axis (fig. 5-72) (Goto et al. 1978). They occur as scattered cells in the normal wood of the oaks and hickories and are abundant in normal elm and hackberry. Barefoot (1963) found that some woods have no identifiable gelatinous fibers and others such as yellow-poplar have only limited amounts regardless of tree lean. He also found that gelatinous fibers were both infrequent and unusual in yellow-poplar. Arganbright and Bensend (1968) studied the relationship of lean to gelatinous fiber development in 36 soft maple trees (red and silver), with lean up to 30°, and found considerable variation. Up to 85.8 percent gelatinous fibers were found on the upper side of one tree leaning 28°. Eleven of the trees, including one leaning 30° contained no gelatinous fibers, however. Goebel et al. (1960) found that hickory trees which split severely on being felled had significantly greater amounts of gelatinous fibers than those that did not split. Relatively large amounts of gelatinous fibers distributed uniformly over the entire cross-section caused severest splitting.

Barefoot (1963), in his study of yellow-poplar trees, found that the fibers varied from a state of extremely limited lignification to one of complete lignification. In all but one instance, unlignified fibers were associated with tension wood. Sorensen and Wilson (1964) studied eccentricity and tension wood in red oak trees leaning naturally and those tipped by forces such as high winds. Tension wood (unlignified fibers) occurred on upper sides in both instances but eccentricity occurred on the upper side only in tipped trees and on the lower side of naturally leaning trees.

Burkart and Cano-Capri (1974) found that in southern red oaks degree of lean did not influence total amount of gelatinous fibers in cross-sectional area but the upper quadrant contained highest concentrations. They suggested grading standing trees according to lean classes and that lumber from the upper side of leaning trees not be used for quality lumber or for veneer.

Tension wood generally is associated with abnormal surfaces (woolly fibers), fuzzy streaks, low crushing strength along the grain, excessive longitudinal shrinkage, buckling of veneers and collapse in lumber (Akins and Pillow 1950). Vick (1960) noted that a normal board 10 feet long shrinks approximately 0.36 inch from green to ovendry while the same length of board containing all tension wood could shrink up to 1.08 inches. Lassen and Cooper (1960) found that of 10,000 bd ft of red oak lumber from southern Illinois, 82 percent contained tension wood, but concluded that warping did not appear to be much of a problem in furniture cuttings. Parham et al. (1977) reported that tension wood from short rotation *Populus* produced paper of inferior strength properties.

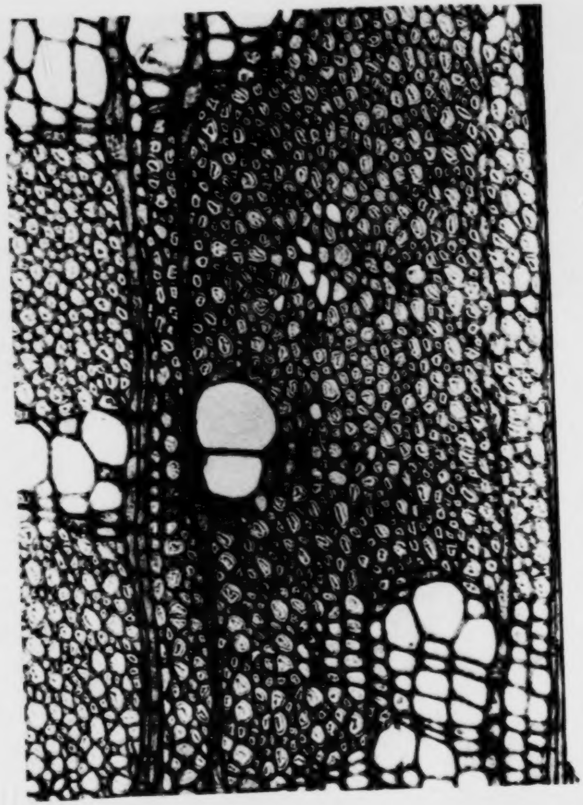

Figure 5-71.—Gelatinous fibers in transverse surface of hackberry. The loosely attached G layer is seen inside the fiber cells as flattened, distorted, and separate. Gelatinous fibers appear to occur normally in hackberry, elms, oaks, and hickories. (Micrograph from W.A. Côté.) 227X

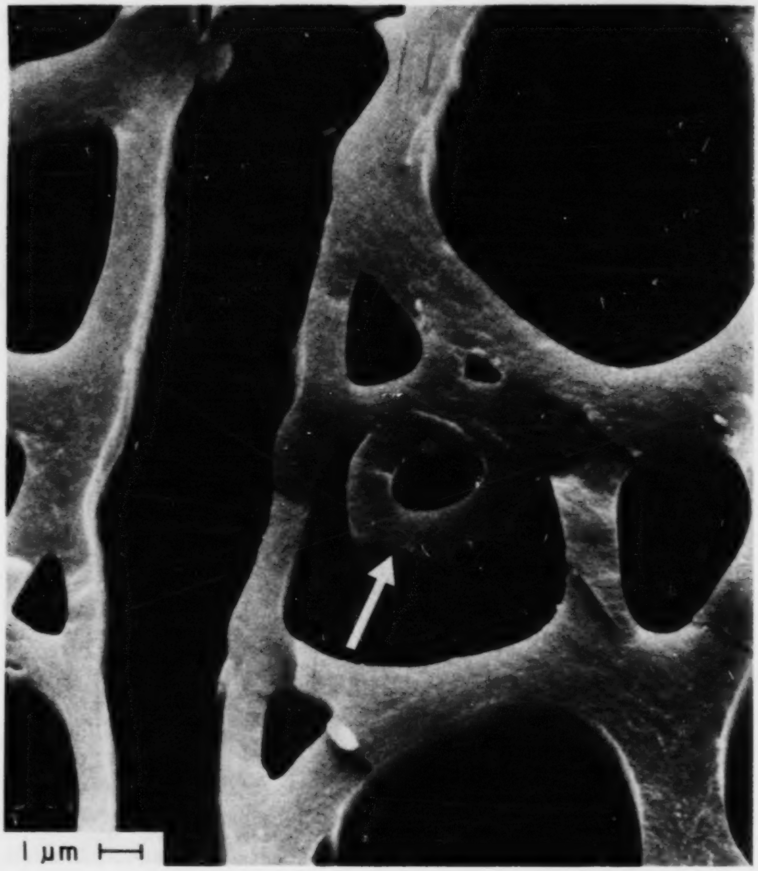

Figure 5-72.—Single gelatinous fiber (center) in hackberry, viewed in transverse section. Wall material fragments of the detached G layer (arrow) indicate nearly vertical alignment of microfibrils in this layer. (Scanning electron charcoal micrograph from W.A. Côté.)

5-8 CELL-WALL ORGANIZATION

As in confiers, cells of normal hardwoods have a **primary wall** and a three-layered **secondary wall** (S1, S2, S3), as shown in figures 5-73, 5-74, and 8-33C. An additional layer, called the **warty layer** and attributed to cytoplasmic remains, to the inside of the S3 layer sometimes is evident (figs. 5-73, 5-74, 5-75). Cell wall layers are most easily differentiated in the thicker-walled, fiber-type cells such as the fiber tracheids, libriform fibers, and vasicentric tracheids. The complexity of hardwood anatomy has discouraged research on cell-wall organization and the literature is sparse.

Kishi et al. (1977, 1979) described three types of standard layered structures in unpitted regions of secondary walls of hardwood vessels. These are: three-layered (S1, S2, S3), one-layered, and multi-layered (more than three). Information on the structure of the primary wall is given in Kishi et al. (1981).

Wheeler and Thomas (1981), in a study of southern red oak and white oak, found that the inclination of the pit apertures (and by inference, the S2 layer of microfibrils), is at 90°, 20-30°, and 20° relative to the longitudinal axis of vessel elements, vasicentric tracheids and fibers, respectively.

Wheeler (1982), in a study of the ultrastructure of red maple using a transmission electron microscope, found that pit apertures of the vessel elements paralleled fibrils of the S2 layer of the cell wall; helical (spiral) thickenings were part of the S3 layer; vessel-ray parenchyma pits were not similar to intervessel pits; all fiber tracheids examined had bordered pits; and there were longitudinal intercellular spaces between fibers. Ray parenchyma cells in red maple do not have well-defined protective layers in the sapwood when they are adjacent to vessels, plasmodesmata channels are not apparent in the parenchyma-parenchyma pits, and there are no pits-to-intercellular spaces in the rays.

Electron microscopy, resolving to about 10 A (an angstron unit is 10^{-4} μm), reveals microfibrils, some 100-300 A in diameter and of indefinite length, comprising the cellulose framework of the cell wall. These are in turn made up of elementary fibrils—presumably the cellulosic strands of smallest possible cross-section—measuring about 35 A in diameter. An elementary fibril in turn consists of cellulose chains. Agreement is not unanimous on organization of microfibrils and elementary fibrils; additional information may be found in discussion related to figure 6-3 and in the following reviews: Lange (1959), Wardrop (1962), Kollmann and Côté (1968, p. 18-20), Berlyn (1970), Stamm (1977), Mühlethaler (1964), Frey-Wyssling (1968), Chafe (1978), Harada (1964), and Meylan and Butterfield (1978).

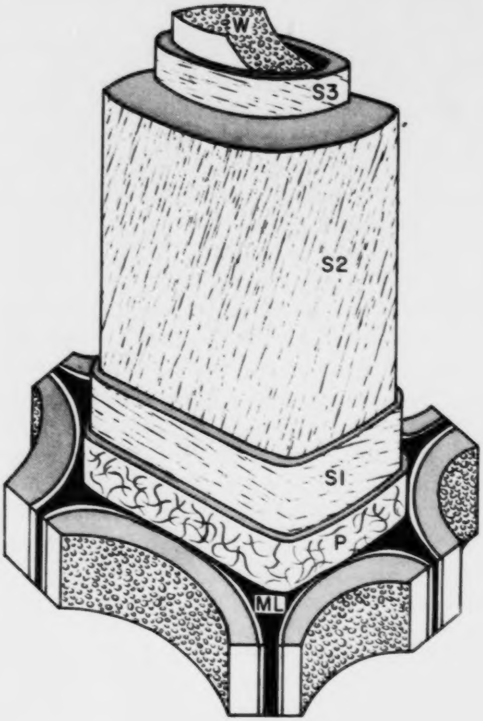

Figure 5-73.—Cell wall organization. Idealized model of typical wall structure of a fiber or tracheid. The cell wall consists of: P-primary wall; S1, S2, S3-layers of the secondry wall; W-warty layer (not always evident); ML-middle lamella, the amorphous, high-lignin-content material that binds cells together. (From Wood Ultrastructure—An Atlas of Electron Micrographs, by W.A. Côté. 1967. By permission of University of Washington Press, Seattle.

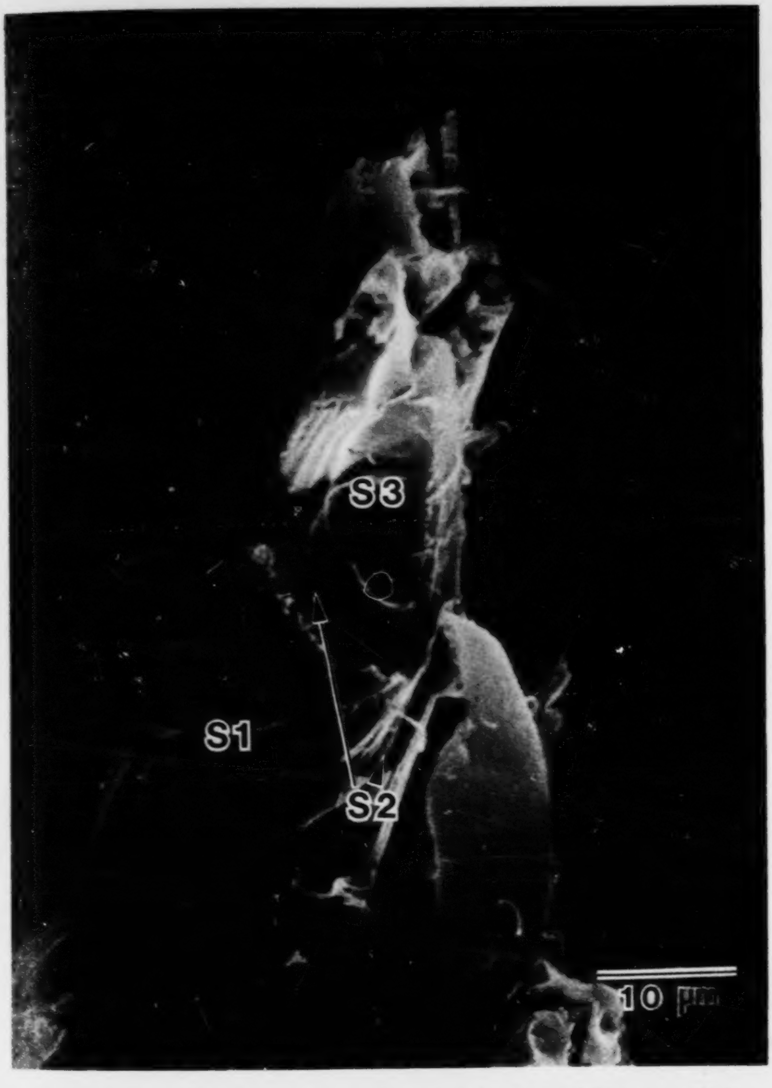

Figure 5-74.—These fibers in a tensile test specimen of hickory exhibit intrawall failure in which all three secondary wall layers can be identified through their fibril orientation. See also figure 8-33C. (Scanning electron micrograph from W.A. Côté.)

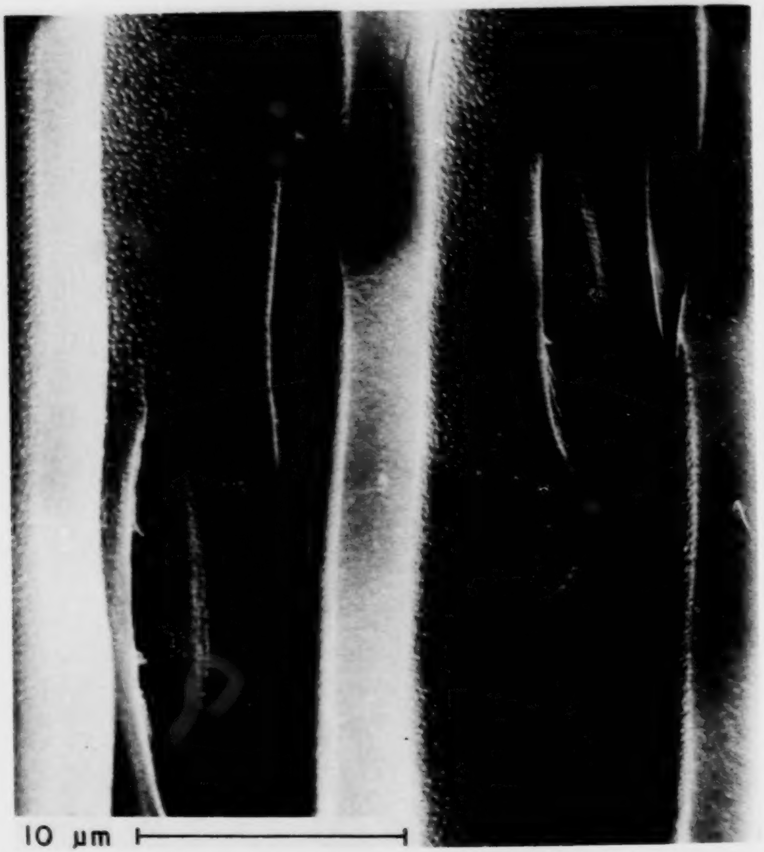

Figure 5-75.—Warty layer in fiber tracheids of yellow-poplar; radial view. Slitlike inner apertures of bordered pits parallel microfibrils in the S2 layer. (Scanning electron charcoal micrograph from W.A. Côté.)

5-9 TISSUE PROPORTIONS

Knowledge of tissue proportions is important to processers of hardwoods, particularly paper makers. Longitudinal parenchyma, ray parenchyma and vessel elements are usually shorter and usually thinner-walled than the fibers; they contribute little to paper strength. Frequently a high percentage of such tissue is lost during washing and screening.

Table 5-3 gives average proportions of elements in 6-inch trees of important species of hardwoods growing among southern pines. These averages are based on 10-tree samples from across the southern range of each species.

Vessel volume of stemwood ranges from a low of 10.5 percent in laurel oak to a high of 46.2 percent in sweetgum. The oaks contain relatively low volumes of vessels. In branchwood, the proportion of vessels also is low in laurel oak (10.5 percent) and high in sweetgum (49.5 percent).

Fiber proportion in stemwood is lowest (about 37 percent) in black oak, blackjack oak, post oak, southern red oak, and sweetgum and highest in green and white ash (about 57 percent). In branchwood, sweetgum has lowest proportion of fibers (35.3 percent) and white ash highest (55.0 percent).

TABLE 5-3.—*Proportions of elements in stemwood and branchwood of 6-inch-diameter hardwoods of 22 species grown on southern pine sites* (Data from Manwiller[1,2])

Species	Vessels	Fibers	Rays	Parenchyma
	Percent			
		STEMWOOD		
Ash, green	14.5	57.3	14.2	14.0
Ash, white	14.5	57.0	14.0	14.4
Elm, American	31.1	42.1	12.0	14.8
Elm, winged	28.2	40.0	15.5	16.2
Hackberry	20.1	50.9	13.6	15.4
Hickory, true	14.7	53.2	18.1	14.0
Maple, red	23.2	50.6	12.8	13.4
Oak, black	14.7	37.1	20.8	27.4
Oak, blackjack	16.1	37.8	21.5	24.6
Oak, cherrybark	11.2	44.8	18.4	25.5
Oak, laurel	10.5	43.3	19.7	26.4
Oak, northern red	15.3	41.3	19.0	24.5
Oak, post	12.4	37.5	22.6	27.6
Oak, scarlet	12.6	44.8	18.2	24.4
Oak, Shumard	12.1	45.7	18.3	23.8
Oak, southern red	14.6	37.8	19.0	28.5
Oak, water	12.8	42.7	18.5	25.9
Oak, white	14.7	41.2	20.7	23.5
Sweetbay	30.1	50.3	15.2	4.4
Sweetgum	46.2	37.6	14.0	2.1
Tupelo, black	38.4	39.8	17.2	4.6
Yellow-poplar	43.3	42.6	11.4	2.7
Average	20.5	44.4	17.0	18.1

See footnotes on following page.

TABLE 5-3.—*Proportions of elements in stemwood and branchwood of 6-inch-diameter hardwoods of 22 species grown on southern pine sites* (Data from Manwiller[1,2])—continued.

Species	Vessels	Fibers	Rays	Parenchyma
	Percent			
	BRANCHWOOD			
Ash, green	15.8	51.4	15.6	17.3
Ash, white	14.0	55.0	14.7	16.4
Elm, American	26.5	45.7	10.2	17.6
Elm, winged	25.9	45.8	12.6	15.7
Hackberry	18.0	52.3	14.6	15.1
Hickory, true	14.9	51.1	16.2	17.8
Maple, red	25.2	43.3	12.5	19.0
Oak, black	15.3	42.3	17.0	25.4
Oak, blackjack	13.2	42.3	21.6	22.9
Oak, cherrybark	12.3	47.9	17.2	22.6
Oak, laurel	10.5	45.2	18.0	26.3
Oak, northern red	14.5	44.1	18.0	23.4
Oak, post	11.1	41.2	15.7	31.9
Oak, scarlet	13.0	46.7	18.1	22.2
Oak, Shumard	10.5	48.6	17.5	23.4
Oak, southern red	12.3	42.6	18.4	26.7
Oak, water	12.8	42.5	18.7	26.0
Oak, white	13.8	42.5	16.3	27.4
Sweetbay	29.6	50.0	14.8	5.5
Sweetgum	49.5	35.3	13.2	1.9
Tupelo, black	36.6	42.8	16.4	4.1
Yellow-poplar	38.8	44.7	12.6	3.9
Average	19.7	45.6	15.9	18.8

[1] Data in files of U.S. Dep. Agric. For. Serv., Study FS-SO-3201-1.42, Pineville, LA.

[2] Averages based on a 10-tree sample of each species; sampling procedure yielded tree-average data for both stemwood and branchwood. Averages do not always sum to exactly 100 percent due to rounding of component values. Tree dimensions are given in Table 3-1 and Table 16-3.

Ray proportion in stemwood is low in yellow-poplar at 11.4 percent and high in post oak, at 22.6 percent. In branchwood, American elm is low (10.2 percent) and blackjack oak is high (21.6 percent). Oaks have a relatively high proportion of ray tissue—18 to 23 percent in stemwood and 16 to 22 percent in branchwood.

Longitudinal (axial) parenchyma varies considerably among the species studied. The stemwood proportion is low in sweetgum at 2.1 percent and high in all the oaks; post oak was highest with 27.6 percent. Sweetgum branchwood is also low in longitudinal parenchyma with 1.9 percent, while white oak contains the greatest proportion at 27.4 percent.

5-10 ANATOMICAL VARIATION

Valid comparisons of all diameter classes of the hardwood species growing in southern pine sites are not available; the data at hand are incomplete, but summarization is useful.

To simplify this presentation on variability, only longitudinal fibers and vessel elements will be considered. Comparisons of cellular dimensions will be restricted to length, radial and tangential diameters, wall thickness, and fibrillar angle in the S2 layer.

FIBER LENGTH

Fiber length affects the strength, surface, and bonding properties of fiber products and is therefore of interest. Long fibers shrink less longitudinally than short fibers (Dadswell and Nicholls 1959). For many purposes, long fibers are more desirable than short. For some purposes, short fibers are required, either alone or in mixture with long fibers.

Among-species variation.—Manwiller's (1974) report on fiber length in stems and branches of 22 species of small hardwoods on southern pine sites provides the most pertinent data. In his study, 10 trees of each species were cut—a total of 220 trees; true hickories were considered as a single species grouping. The sample (table 5-4) was restricted to trees 6 inches dbh (5.5-6.5 inches) outside bark, since large volumes of hardwoods on pine sites occur in small-diameter classes. Sampling locations were broadly distributed throughout that portion of each species' range occurring in the 11-state area extending from Virginia to Northern Florida and west to Arkansas and eastern Texas. One tree of a species was cut at a location, and all locations were on southern pine sites. Stemwood and branchwood (down to 0.5 inch diameter outside bark) were separately sampled to yield tree-average values. Sample wedges were chopped into wafers and macerated. Length of fibers (fiber tracheids and libriform fibers) was measured on an ampliscope.

The species are arranged in Table 5-4 in order of increasing length of fibers in stemwood. Differences of 0.1 mm or more are significant (at the 0.05 level) in stemwood, while in branchwood, differences of 0.09 mm or more are significant. Red maple has conspicuously shorter fibers (0.83 mm in stemwood and 0.66 mm in branchwood) than the other species. The longest fibers are in sweetgum (1.54 mm and 1.20 mm) and black tupelo (1.76 mm and 1.40 mm).

For each species investigated, fiber length averaged significantly shorter in branches than in stems. For all species combined, branch mean fiber length was 24.4 percent shorter than that of the stem. Branch means ranged from 20.5 percent shorter in red maple and black tupelo, to 30.2 percent shorter in yellow-poplar.

Table 5-4.—*Stem and branchwood fiber lengths in 6-inch-diameter hardwoods growing on southern pine sites* (Data from Manwiller 1974[1])—continued.

Species	Tree mean age	Mean fiber length	Within-tree standard deviation	Among-tree Standard deviation
	Years	----------	*mm*	----------
			STEMWOOD	
Red maple	40	0.83	0.143	0.047
Hackberry	28	1.12	.201	.065
Blackjack oak	39	1.14	.223	.105
Green ash	37	1.16	.257	.087
Post oak	51	1.18	.233	.052
White oak	41	1.22	.216	.058
White ash	40	1.22	.258	.099
Sweetbay	39	1.24	.254	.082
Winged elm	47	1.25	.196	.068
Northern red oak	40	1.27	.242	.092
Water oak	39	1.27	.261	.102
Hickory, true (*Carya* sp.)	54	1.29	.249	.116
Southern red oak	35	1.29	.258	.083
Black oak	39	1.30	.260	.067
Cherrybark oak	32	1.30	.273	.102
American elm	40	1.30	.241	.115
Scarlet oak	33	1.30	.248	.068
Shumard oak	34	1.31	.264	.113
Laurel oak	33	1.34	.254	.086
Yellow-poplar	27	1.39	.296	.092
Sweetgum	29	1.54	.302	.123
Black tupelo	59	1.76	.324	.140
Average		1.27		

See footnote at end of table

The tree selection procedure insured the sampling of the wide range of growing conditions and tree ages for 6-inch trees on pine sites. Tree age varied from a mean of 27 years in yellow-poplar to 59 years in black tupelo; the average age for all species was 39 years. Therefore, the "among-tree" standard deviations listed in Table 5-4 probably are close to the maximums for weighted stem averages to be found among trees on pine sites. For both stemwood and branchwood, variability within the tree averaged 2.7 times greater than that among trees within a species. Standard deviation within trees averaged 0.248 mm in stemwood, while among trees within a species, it averaged 0.089; for branchwood, the corresponding values were 0.204 and 0.079.

Fiber lengths for 14 of the species in table 5-4 are given in Panshin and deZeeuw's (1980) text, and Bergman (1949) has reported values for 12 of the same species; but differences in stem sampling methods probably render comparisons invalid.

By definitions applied to dicotyledonous woods (Anon. 1937), red maple

TABLE 5-4.—*Stem and branchwood fiber lengths in 6-inch-diameter hardwoods growing on southern pine sites* (Data from Manwiller 1974[1])—continued.

Species	Tree mean age	Mean fiber length	Within-tree standard deviation	Among-tree Standard deviation
	Years	-----------	-----*mm*-----	-----------
			BRANCHWOOD	
Red maple	40	0.66	0.121	0.058
Hackberry	28	.86	.189	.066
Blackjack oak	39	.88	.175	.065
Green ash	37	.84	.181	.064
Post oak	51	.93	.184	.072
White oak	41	.88	.186	.046
White ash	40	.87	.192	.084
Sweetbay	39	.97	.210	.099
Winged elm	47	.93	.193	.077
Northern red oak	40	.90	.191	.067
Water oak	39	.98	.211	.089
Hickory, true (*Carya* sp.)	54	.98	.220	.095
Southern red oak	35	.96	.217	.087
Black oak	39	.98	.203	.068
Cherrybark oak	32	.94	.232	.075
American elm	40	.99	.237	.112
Scarlet oak	33	.98	.204	.079
Shumard oak	34	.99	.216	.081
Laurel oak	33	1.01	.223	.063
Yellow-poplar	27	.97	.193	.105
Sweetgum	29	1.20	.240	.059
Black tupelo	59	1.40	.268	.134
Average		.96		

[1] Data are based on a 10-tree sample of each species; species are listed according to mean fiber length in stemwood.

stem fibers are "moderately short", those of black tupelo are "moderately long", and those of the other 20 species are "medium-size". For branchwood, fiber lengths are classified as "very short" in red maple, while the remaining species are classified as "moderately short" (0.7 to 0.9 mm) to "medium-size" (0.9 to 1.6 mm).

Stemwood averages for fiber length in the 6-inch trees (averaging 39 years of age) studied by Manwiller are perhaps shorter than those observed in older and larger trees from more favorable sites. For example, Taylor (1968b) reported a 1.72 mm stemwood average for six yellow-poplar cut in the Piedmont section of North Carolina.

In 321 trees of five southern hardwoods 20-60 years old collected from a variety of sites throughout the Gulf States and southern Atlantic coastal states, Kellison and Zobel[4] found substantial differences between species; their data on four of the species (Table 5-5) are presented as stem-average values for growth sheaths 1 through 15 and sheaths 16 and older.

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[4] Kellison, R.C. and B.J. Zobel. Wood and fiber properties of five southern hardwoods. Paper given at the 25th annu. meet., For. Prod. Res. Soc., Pittsburgh, PA., June 27-July 1, 1971. 17 p. See also: Jett and Zobel (1975).

Not illustrative of tree-average values, but indicative of species differences in average length of mature fibers (growth increments 21 and older sampled at breast height) are the following data from Taylor (1977a):

Species	Number of locations	Average fiber length
		mm
Shagbark hickory	3	1.28
Post oak	6	1.29
Mockernut hickory	6	1.37
Water oak	5	1.42
Southern red oak	6	1.53
Sweetgum	6	1.72
Yellow-poplar	4	1.85
Black tupelo	6	1.88

At each location, 10 trees were sampled; each average therefore represents 30-60 trees of a species. Trees measured about 11 inches in dbh and were collected from a variety of sites in Arkansas, Louisiana, Mississippi, and Alabama.

Within-species variation.—From the foregoing data, it is evident that fiber length varies substantially among species. Variation among trees within species is also substantial. A measure of this variation is given by the stemwood and branchwood columns headed *among-tree standard deviation* in Table 5-4. The Kellison-Zobel data (Table 5-5) also illustrate large among-tree variation; for example, young sweetgum trees had a range of stem-average fiber lengths from 1.35 to 2.22 mm.

In another study (Taylor 1968b), six mature dominant yellow-poplar trees from the Piedmont section of North Carolina had stem-average fiber lengths ranging from 1.59 to 1.89 mm; the longest fibered three had longest fibers at all heights, while that with the shortest average fiber length had shortest fibers at all heights except the 20-foot level where it ranked second shortest. In a different, but related study, Taylor (1965) found no significant differences in a tree-average fiber length that could be attributed to plot or to physiographic area in North Carolina (Coastal Plain, Piedmont and Mountains).

In an Alabama study of 435 sweetgum trees, however, geographic location, i.e., latitude, was significantly related to fiber length sampled at breast height in the 20th annual ring from the pith (table 5-6); longer fibers were associated with locations having longer growing seasons, and more summer rainfall (Hunter and Goggans 1969). In this study, sweetgum trees in northern Alabama had shortest fiber (1.790 mm), and those in southeastern Alabama the longest (1.827); trees in southwestern Alabama were intermediate (1.807).

Breast height fiber length of dominant and co-dominant sweetgum studied by Webb (1964) in stands from Florida to Virginia, increased somewhat from north to south (fig. 5-76). Trees within stands varied significantly in fiber length (fig. 5-77). Randel and Winstead (1976) concluded from growth chamber studies of sweetgum from the United States and Central America that fiber lengths varied inversely with latitude of origin.

TABLE 5-5.—*Stem-average fiber dimensions, and range, for annual ring sheaths 1 through 15 and annual ring sheaths 16 and older in 4 hardwood species collected from a variety of southern sites* (data from Kellison and Zobel[1])

Species	Length		Radial Fiber diameter		Tangential double cell wall thickness		Radial lumen diameter		Runkel ratio[2]	
	1-15	16+	1-15	16+	1-15	16+	1-15	16+	1-15	16+
	mm		*um*							
Sweetgum	1.90 1.35-2.22	2.13 1.72-2.41	28.90 24.80-32.04	30.15 27.00-36.91	15.30 12.94-19.16	16.74 13.72-20.04	13.63 10.67-18.01	13.49 9.66-17.97	1.12	1.24
Green ash	1.24 0.97-1.57	1.41 1.13-1.82	20.16 14.00-25.83	23.52 18.50-27.50	6.80 5.00-8.66	7.74 6.00-10.34	13.58 7.33-18.50	15.73 18.50-27.50	.50	.49
Red maple	0.93 0.76-1.08	1.02 0.87-1.29	21.93 18.50-26.83	24.07 20.33-28.17	6.94 5.00-8.66	7.72 5.66-9.84	15.00 11.50-20.50	16.42 13.00-28.17	.46	.48
Water-willow oak	1.41 1.12-1.60	1.60 1.33-1.83	18.61 13.83-23.50	20.61 16.83-23.33	10.90 8.34-17.66	12.62 10.34-17.66	8.03 6.00-11.17	8.20 6.17-11.67	1.36	1.54

[1] Kellison, R.C. and B.J. Zobel. Wood and fiber properties of five southern hardwoods. Paper given at the 25th annu. meet., For. Prod. Res. Soc., Pittsburgh, Pa., June 27-July 1, 1971. See also: Jett and Zobel (1975).

[2] Twice the cell wall thickness/lumen diameter.

TABLE 5-6.—*Fiber lengths in the 20th annual ring, breast height, in sweetgum trees, related to latitude in Alabama* (Data from Hunter and Goggans 1969)

Latitude	Mean fiber length	Statistical significance[1]			
Degrees and minutes	*mm*				
33° 45′	1.421				
34° 30′	1.546				│
32° 15′	1.752				│
32° 30′	1.763			│	│
32° 45′	1.772			│	│
34° 00′	1.776			│	│
35° 00′	1.791			│	│
33° 00′	1.792			│	│
34° 45′	1.796			│	│
33° 30′	1.803		│	│	│
33° 15′	1.811		│	│	│
34° 15′	1.814		│	│	│
32° 00′	1.827		│	│	
31° 30′	1.834		│	│	
31° 15′	1.838	│	│	│	
31° 45′	1.878	│	│		
31° 00′	1.921	│			

[1] At 5 percent level by Duncan's new multiple range test; values opposite the same line are not significantly different.

Sweetgum trees sampled from Texas to North Carolina, however, showed no significant differences in fiber dimensions attributable to geographic location (Johnson and McElwee 1967).

In a comparison of upland sites with bottomland sites, Ezell and Stewart (1981) measured some 80,000 fiber lengths from three geographical areas. Fibers were significantly longer in upland sites in one area, and significantly shorter in another. They concluded that the magnitude and nature of variation between upland and bottomland sites appear to be geographically isolated.

Northern red oak sampled at breast height throughout its range in the United States showed no clear trend relating fiber length to geographic location, although significant differences were observed among sampling locations (Maeglin 1976).

Cherrybark oaks in west Tennessee and central Mississippi had fiber lengths (tree average for 20-21st rings and 38-39th rings at breast height) ranging from 1.08 to 1.98 mm; tree-to-tree variation was broad, while geographic variance was small (Farmer 1969).

The between-tree variations described are in part based on site and stand circumstances and in part on genetic considerations. Webb (1964) concluded that wide tree-to-tree variation in every stand or population of sweetgum is contributed to by a large measure of genetic variation. Smith (1967) concluded from a survey of the literature that fiber length is genetically controlled. Known inheritance values on fiber length of hardwoods are few, but those reported are strong (Zobel 1965).

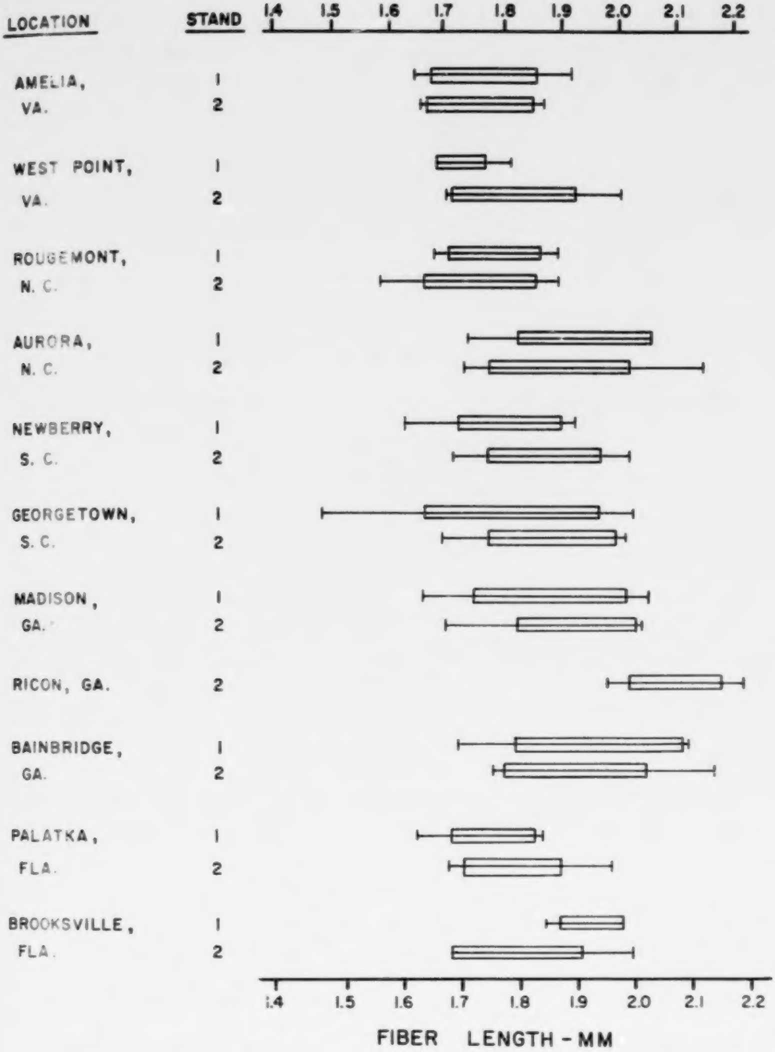

Figure 5-76.—Within-stand and geographic variation in sweetgum fiber length measured at breast height in annual rings 18, 19, and 20. Locations arranged to read down the page from north to south. (Drawing after Webb 1964, p. 64.)

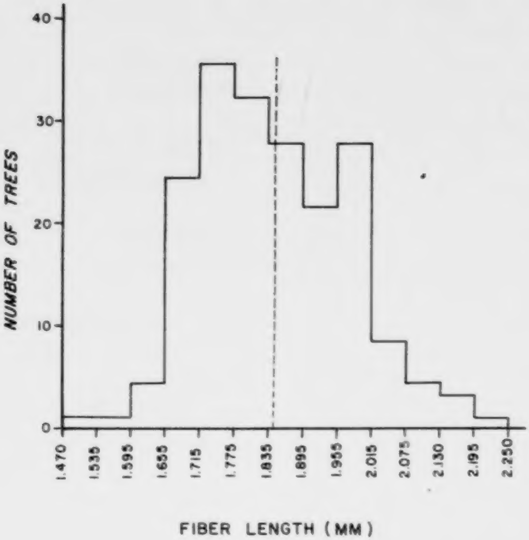

Figure 5-77.—Frequencies of tree-average fiber lengths in sweetgum breast-height samples of rings 18, 19, and 20. Trees sampled totaled 195. (Drawing after Webb 1964, p. 75.)

Readers desiring additional information on between-tree variability in fiber length should find the following additional publications of interest.

Reference	Species	Subject
Thorbjornsen 1961	Yellow-poplar	Improvement of the species
Thor 1966	Yellow-poplar	Improvement of the species
Hamilton and Chesser 1969.	White oak and sweetgum	Xylary aberrations induced by ionizing radiation
Foulger et al. 1972........	White ash	Effect of nutrient concentration on stem anatomy
Thor and Core 1972.......	Yellow-poplar	Effect of fertilization and irrigation on fiber length
Wooten et al. 1973........	Yellow-poplar	Effect of tree release on fiber length

Within individual trees, the trend in fiber length in succesive annual rings tends to follow the normal growth curve of a tree. Fibers are short in initial annual rings. They increase in length with distance from the pith while the tree is vigorous, remain constant and may decrease as tree vigor declines. In general, fibers (averaged over entire stem cross-sections) are longest near ground level, and are somewhat shorter with increasing height in the stem. Within individual annual rings, fibers are shortest in initial earlywood and longest in latewood. In the following paragraphs are data specific to southern hardwoods.

Radial variation within trees.—Taylor sampled fiber lengths in pairs of 11-inch-dbh hardwood trees of eight species from six mid-south sites. In six of the species fiber length increased from the pith to a maximum in growth rings 30 to 40 and decreased slightly thereafter (fig. 5-78). In the sweetgum and black tupelo trees studied, however, fiber length increased from pith to bark. These patterns were found at all heights sampled (fig. 5-79). Data for southern red oak (fig. 5-80) typify the pattern of fiber-length radial variation in the six species whose fiber length peaked between pith and bark.

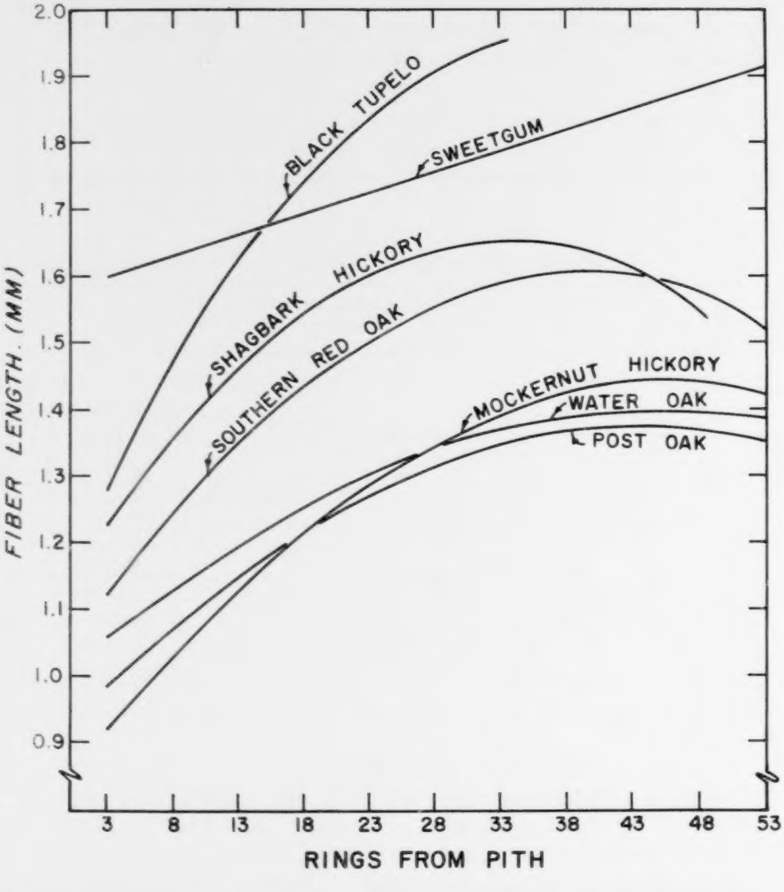

Figure 5-78.—Fiber lengths at 5-foot height in stemwood of seven species related to number of annual growth rings from the pith. (Drawing after Taylor 1979.)

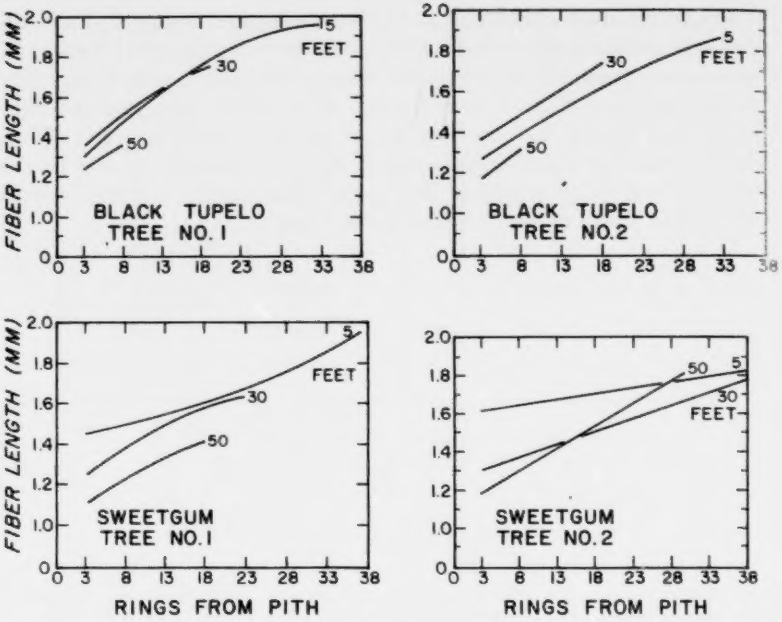

Figure 5-79.—Fiber length related to number of annual rings from the pith at 5-, 30-, and 50-foot heights in black tupelo (top) and sweetgum (bottom); trees were 11 inches in dbh and sampled in the mid-South. (Drawing after Taylor 1979.)

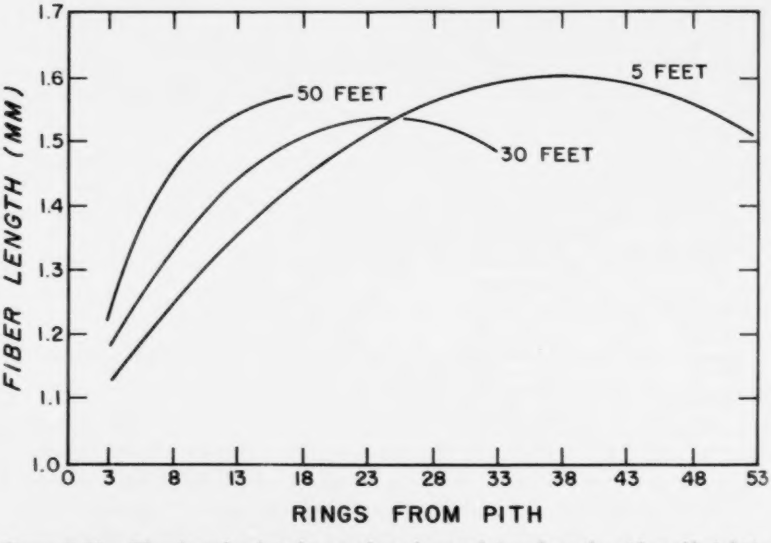

Figure 5-80.—Fiber length related to number of annual rings from the pith and height in an 11-inch-dbh southern red oak tree sampled in the mid-South. (Drawing after Taylor 1979.)

Bosshard's (1951) studies of European ash (*Fraxinus excelsior* Linn.) indicated that fiber length increases from the pith toward the bark for the first 30 years and then decreases. Similarly, seventeen white ash sampled from a Georgia plot had fiber lengths at breast height as follows (McElwee et al. 1970):

Ring from pith	Average
	------*mm*------
1	0.79 ± 0.21
3	.90 ± .20
10	1.18 ± .25
25	1.14 ± .14

For green ash, Jett and Zobel (1975) reported that annual increment sheaths 1 through 15 years averaged (over stem height) 1.24 mm in fiber length, while annual increment sheaths 16 years and older averaged 1.41 mm. In a single 23-year-old, 7-inch green ash tree from Watkinsville, Georgia, Saucier and Hamilton (1967) found that fiber length increased rapidly with age from pith, but height in tree was of lesser importance (fig. 5-81; number of rings from the pith was linearly related to the ratio: *rings from pith/fiber length*.

Shagbark hickory fibers increased in length from the pith outward for the first 20 years, but their lengths remained nearly constant thereafter (Prichard and Bailey 1916); this trend was observed in a 60-year-old sprout and in 65- and 255-year-old trees of seedling origin.

In breast-height samples of red maple, annual ring sheaths 1-15 had fibers averaging 0.93 mm long; in ring sheaths 16 years and older they averaged 1.02 mm (Jett and Zobel 1975).

Of the southern oaks, data are available on six species. Breast-height cores of 30 cherrybark oaks from west Tennessee and Mississippi had average fiber length of 1.46 mm in annual rings 20 and 21, while rings 38-39 averaged 1.53 mm; fiber length increased rapidly between rings 10 and 30, but then leveled off; a few very old trees reverted to shorter fibers in their last rings (Farmer and Nance 1969).

Black oak and scarlet oak butt logs cut in Mississippi and sampled at their top ends yielded average fiber lengths as follows (McGinnes and Ralston 1967):

Species	Fiber Length	
Species	Rings 1-10	Rings 11 and outward
Black oak.................	1.30	1.63
Scarlet oak................	1.32	1.69

In water oak, annual ring sheaths 1-15 had fibers averaging 1.41 mm long, while fibers in ring sheaths 16 years and older averaged 1.60 mm (Jett and Zobel 1975).

Taylor's (1979) data on 11-inch-dbh water oak, post oak, and southern red oak show similar trends of fiber length increasing curvilinearly with number of rings from the pith, reaching maximums in rings 20 to 45 (figs. 5-78 and 5-80).

Dominant and co-dominant southern red oaks (6 trees, 12 inches in dbh or larger from Durham County, North Carolina) yielded the following regression equation for fiber length at any stem location as a function of percent of total tree height (f_h = percent of total height divided by 10 and rounded to whole number) and number of annual rings from the pith (Hamilton 1961):

$$\begin{aligned}\text{Fiber length, mm} = \; & 0.9907 \\ & + .0861\, f_h \\ & + .0150 \text{ age from pith, years} \\ & - .007752\, f_h^2 \\ & - .000105 \text{ age from pith}^2 \\ & - .000801 \text{ (age from pith) } (f_h^2)\end{aligned} \tag{5-1}$$

This equation accounted for 75 percent of the variation. For more ready visualization, results are plotted in figure 5-82. Variation between trees was considerable (fig. 5-83).

Sugarberry trees from the Delta Experimental Forest near Stoneville, Mississippi (codominant, about 75 feet tall, and approximately 45 years old) analyzed at 5, 25, and 45 foot heights yielded regression equations that accounted for more than 90 percent of the observed variation in fiber length (Taylor 1971); at the two lower heights, fiber lengths diminished in the outermost annual rings (fig. 5-84).

Several investigators have confirmed that sweetgum fiber length increases with distance from pith and proximity to bark, up to at least age 50 (e.g., see figs. 5-78 and 5-79). Annual ring sheaths 1 to 15 years old had fibers 1.90 mm long, while fibers in ring sheaths 16 years and older averaged 2.13 mm (Jett and Zobel 1975). Twenty-five sweetgum trees sampled from a Georgia plot had fiber lengths at breast height as follows (McElwee et al. 1970):

Ring from pith	Average
	------*mm*------
1	1.33 ± 0.15
3	1.51 ± .20
10	1.90 ± .30
25	1.87 ± .25

In breast-height samples of 140 sweetgum trees from east Texas to North Carolina, fiber length averaged 1.81 mm in the 15th ring, and was 1.95 mm in the 30th (Johnson and McElwee 1967).

In breast-height samples of sweetgum trees growing from Florida to Virginia, fiber length was shortest near the pith and increased with number of rings from the pith (fig. 5-85). Chow (1961), in a very detailed study of two Louisiana sweetgums, found a similar near-straight-line relationship. Saucier and Hamilton (1967) observed a like trend in green ash (fig. 5-81). In a sweetgum tree leaning 20 degrees that developed an eccentric stem cross section, Chow (1971) found that mean fiber length across the long axis (tension wood) was 2.17 ±0.30 mm; that across the short axis was significantly shorter—2.05 mm ±0.31 mm.

Yellow-poplars sampled at breast height (63 trees from Tennessee and southeast Kentucky) had fiber lengths ranging from about 1.4 mm near the pith to about 2.1 mm at 32 rings distant from the pith (fig. 5-86). Six yellow-poplar from the Piedmont of North Carolina had even shorter fibers near the pith but displayed the same trend (fig. 5-87).

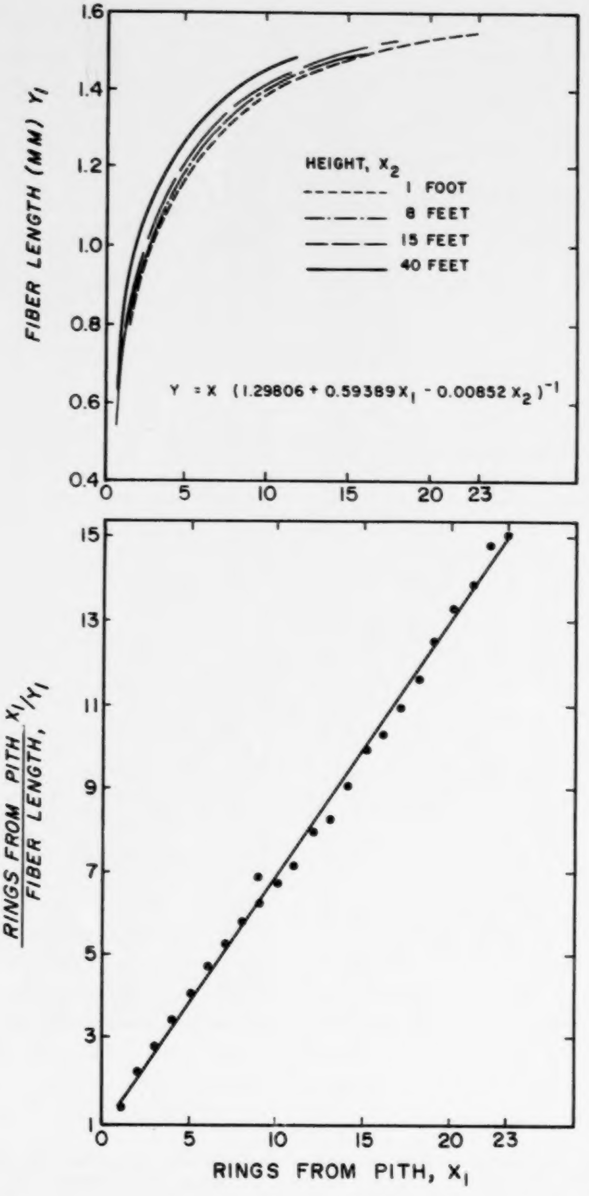

Figure 5-81.—Fiber length in green ash stemwood related to rings from pith. (Top) At four heights. (Bottom) Ratio of *number of rings from pith/fiber length* linearly related to number of rings from pith. (Drawings after Saucier and Hamilton 1967.)

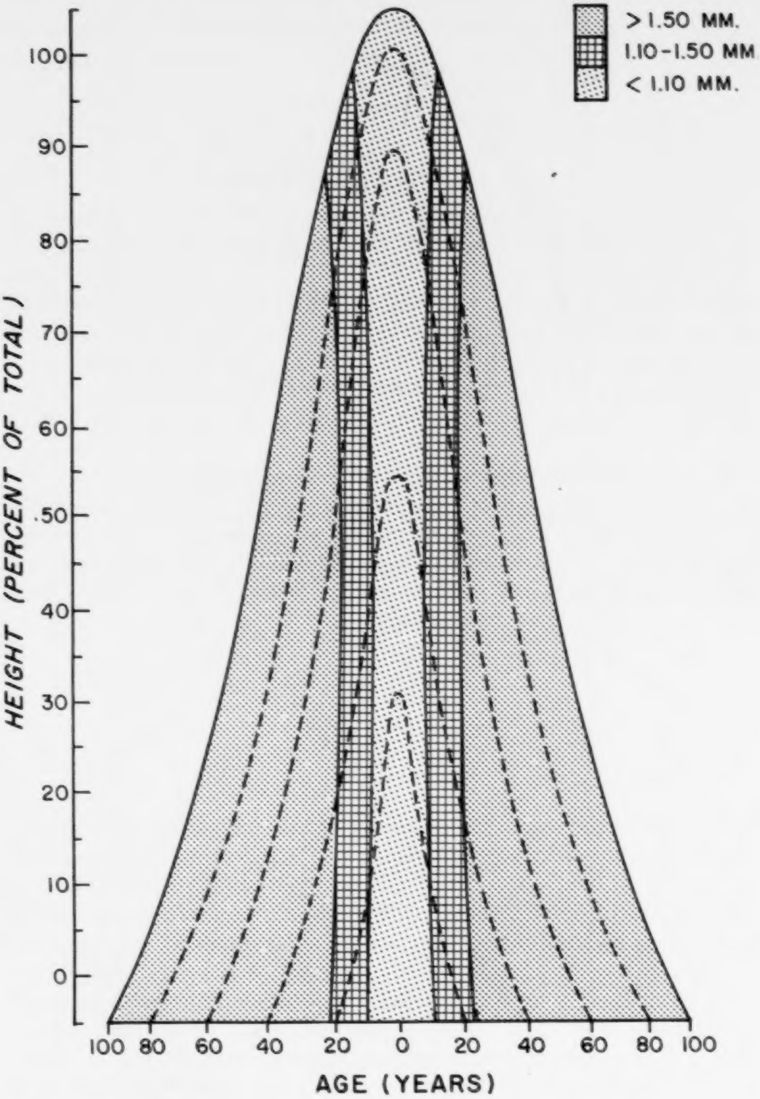

Figure 5-82.—Variation in fiber length (mm) of southern red oak as a function of number of rings from the pith and height in the tree. (Drawing after Hamilton 1961.)

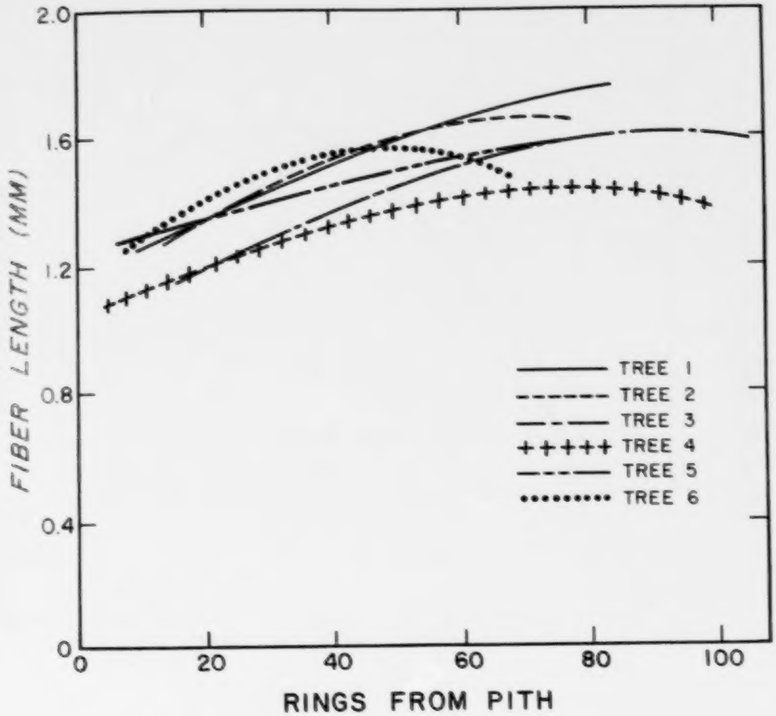

Figure 5-83.—Stemwood fiber length of southern red oak, sampled 1 to 3 feet above ground level, related to number of annual rings from the pith. Each curve represents a single tree. (Drawing after Hamilton 1961.)

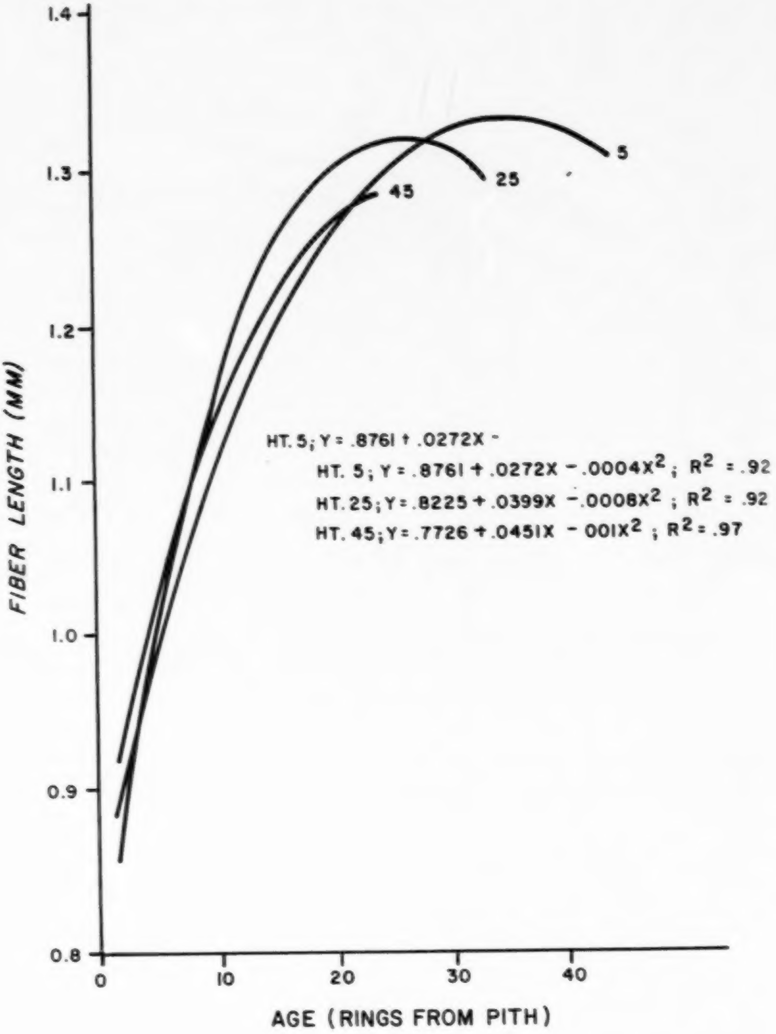

Figure 5-84.—Fiber length (Y) in sugarberry trees at three heights (5, 25, and 45 feet) related to number of rings from pith (x). (Drawing after Taylor 1971.)

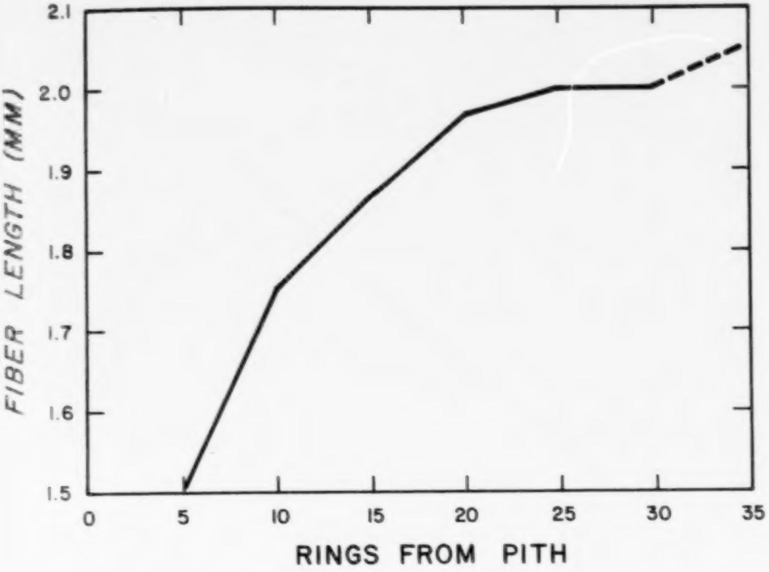

Figure 5-85.—Fiber length at breast height in sweetgum. Broken portion of curve from 9 trees; solid portion based on values from 15 trees. (Drawing after Webb 1964.)

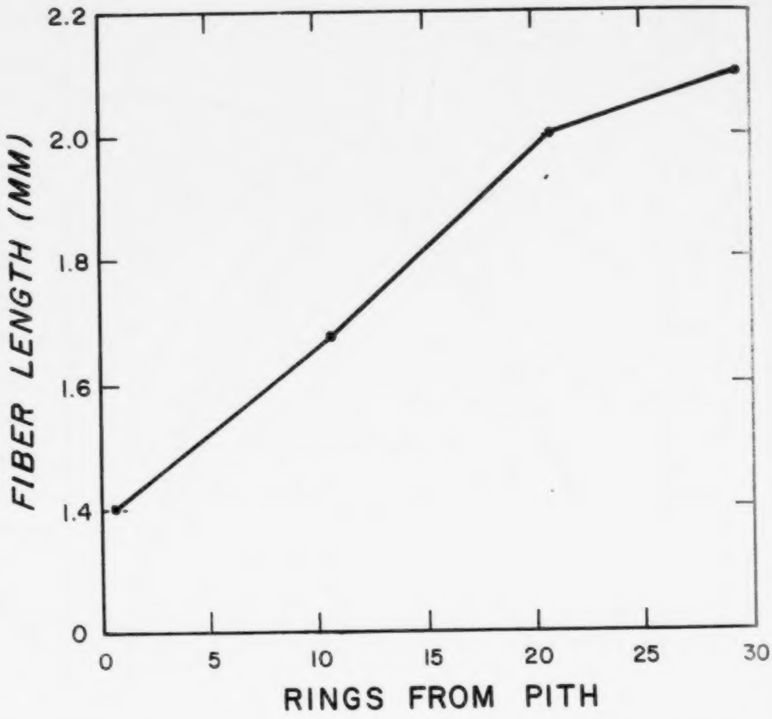

Figure 5-86.—Fiber length at breast height in yellow-poplar related to number of rings from the pith. (Drawing from Thorbjornsen 1961.)

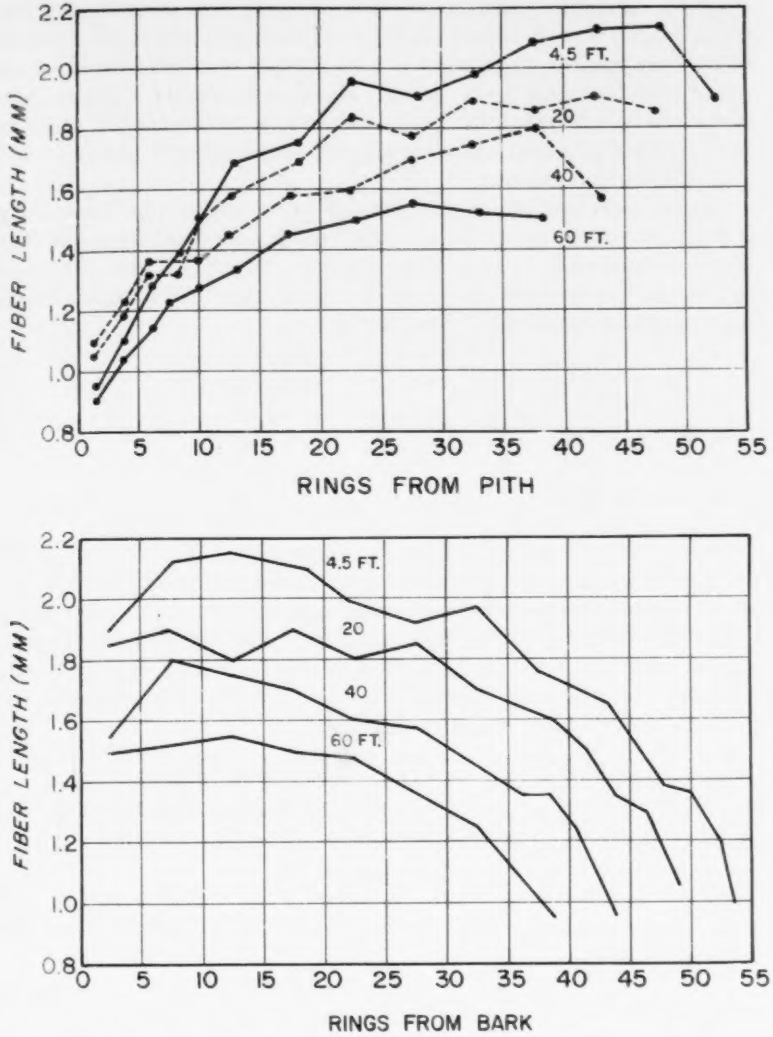

Figure 5-87.—Fiber length of yellow-poplar as a function of height in the tree, and (top) rings from the pith, and (bottom) rings from the bark. (Drawing after Taylor 1968b.)

Height variation within trees.—The foregoing data establish that fiber length—at any level in a stem—is positively correlated with number of rings distant from the pith. Since cross sections at upper stem levels contain fewer annual rings than lower levels, average fiber length variation across an upper stem section should be less than in a lower stem section. This rationale should be valid if fiber lengths within annual ring sheaths remain constant or diminish with increased height in the stem.

The few data available suggest that this is the case in some species. For example, in the 20th annual ring sheath in from the bark of yellow-poplar, fiber length averaged about 2.05 mm at breast height, 1.87 mm at 20 feet, 1.69 mm at 40 feet, and 1.48 mm at 60 feet (fig. 5-87). Height-related data for yellow-poplar are summarized as follows (Taylor 1968b):

Height in stem	Average fiber length across stem section
Feet	*mm*
4.5	1.91
20.0	1.77
40.0	1.61
60.0	1.45

Taylor's (1979) data for black tupelo and sweetgum (fig. 5-79) indicate that fibers at 50-foot height in these species are shorter than those at 30 feet, and usually shorter than those at 5-foot height.

Ezell and Schilling (1979) measured lengths of some 80,000 fibers of sweetgum on upland and bottomland sites from three areas. Fiber length consistently decreased with height and increased from pith outward. Radial variation was less consistent than the vertical variation.

In Webb's (1965) study of 15 sweetgum trees, he found that fiber length at stump height averaged about 1.85 mm; at 50 feet it averaged 1.45 mm (fig. 5-88). Chow's (1961) two Louisiana sweetgum trees also had shorter average fiber length in upper stem sections but differences were smaller, i.e., only 0.1 to 0.2 mm difference between stump height and 40 feet.

Data of McElwee et al. (1970) on white ash, as well as sweetgum, also support the concept that average fiber length is inversely correlated with height in tree (fig. 5-89).

Taylor (1979), in his study of 11-inch dbh hardwoods from the mid-South, found that fiber length in southern red oak increases more rapidly, and attains maximum length after fewer annual growth rings, at upper heights in the stem than at lower (fig. 5-80).

Because sprout growth of hardwoods may ultimately be utilized for pulp or board manufacture, fiber length variation with sprout height is of interest. In seven one-year-old red maple sprouts in Georgia (2.1 to 7.3 feet high) fiber length decreased significantly from about 0.6 mm at the base to about 0.4 mm at the apex (Saucier and Taras 1966).

In mature green ash (fig. 5-81) and sugarberry (fig. 5-84), however, the trend is less clear. In these species, fiber lengths in annual ring sheaths may increase with height in stem from breast height to some intermediate height and then may

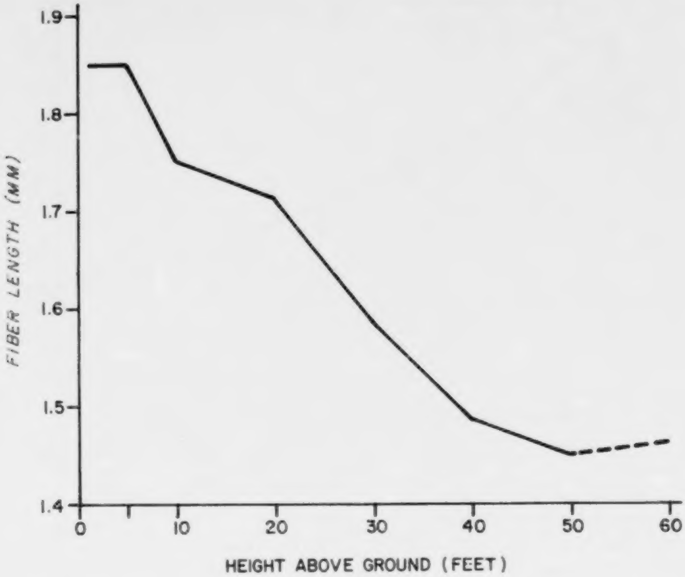

Figure 5-88.—Variation in fiber length of sweetgum with height above ground as determined from wedge-shaped samples from 15 trees. (Drawing after Webb 1964, page 31.)

diminish; such a pattern was also reported by Prichard and Bailey (1916) for shagbark hickory.

Variation across annual ring.—Within annual rings of hardwoods, fiber length increases from earlywood through first-formed latewood and then may tend to decrease in last-formed latewood (Bosshard 1951; Bisset and Dadswell 1949, 1950).

Taylor's (1963) data from breast-height samples of five yellow-poplars from the Piedmont section of North Carolina support the trends just described, but show no diminution of fiber length in last-formed latewood (fig. 5-90); he concluded that in yellow-poplar, last-formed latewood fibers are about 1/3-mm longer than those of first-formed earlywood, the increase being linear across the ring. Webb (1964) found, however, that last-formed latewood in sweetgum has shorter fibers than earlier-formed latewood (fig. 5-91).

In a later study, Taylor (1976) sampled seven additional hardwood species (annual rings 5 and 30, at a level 10 feet above the ground). In all of these species the trend was curvilinear; and in most, fiber length varied more in mature rings than in juvenile rings; regression equations developed accounted, in most cases, for more than 80 percent of the observed variation (figs. 5-92 through 5-98). Variation patterns were different among species and from ring-to-ring within the same tree. Mature wood fibers of all species were longer than juvenile-wood fibers. Taylor found (figs. 5-92 through 5-98) that in mature wood of most species, a maximum length is attained in latewood after which fiber length

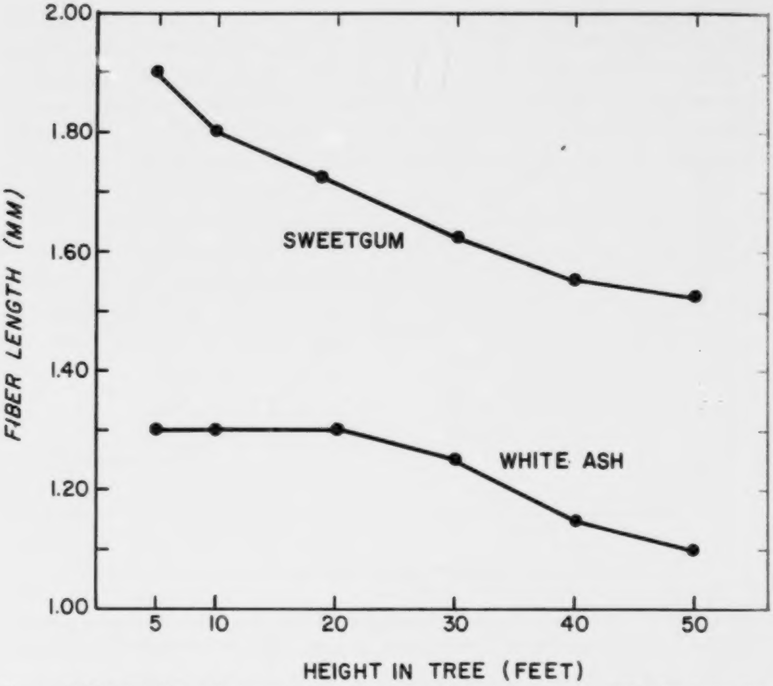

Figure 5-89.—Variation in sweetgum and white ash fiber lengths, in 10th ring from the pith, as a function of height in tree; data are based on ten trees of each species (Drawing after McElwee et al. 1970.)

decreases. In those species in which the fiber length did not decrease (southern red oak and post oak), the rate of increase was greatly reduced.

Correlation of fiber length with other factors.—Taylor (1968b) found that long fibers in yellow-poplar were associated with narrow annual rings and with dense wood having thick fiber walls. Similarly, in one study of sugarberry, long fibers were associated with narrow rings. In the same study, fiber length in sugarberry was found greatest in tissue with large vessel volume and low fiber volume (Taylor 1971).

In sweetgum, Farmer (1969) found a weak negative correlation between width of ring and fiber length, i.e., long fibers were associated with narrow rings. In Johnson and McElwee's (1967) study of sweetgum, they observed that fiber length was positively correlated with fiber diameter and wood specific gravity.

Webb (1964) concluded from his study of sweetgum that neither specific gravity nor growth rate is correlated with fiber length in individual trees; but geographic areas with fast growing trees also grow sweetgum with the longest fibers. Hunter and Goggans (1969) found no important relationship between fiber length and specific gravity of sweetgum grown in Alabama.

Finally, fibril angle was found negatively correlated with fiber length in white ash (Hiller 1968).

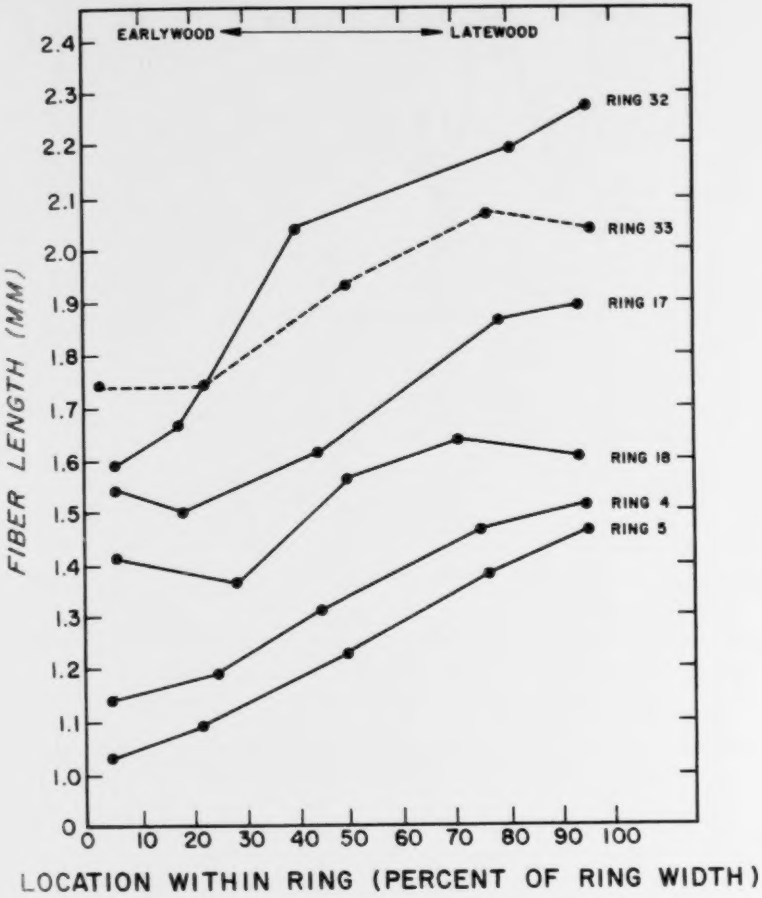

Figure 5-90.—Variation in yellow-poplar fiber length across breast-high annual rings in one tree. (Drawing after Taylor 1963.)

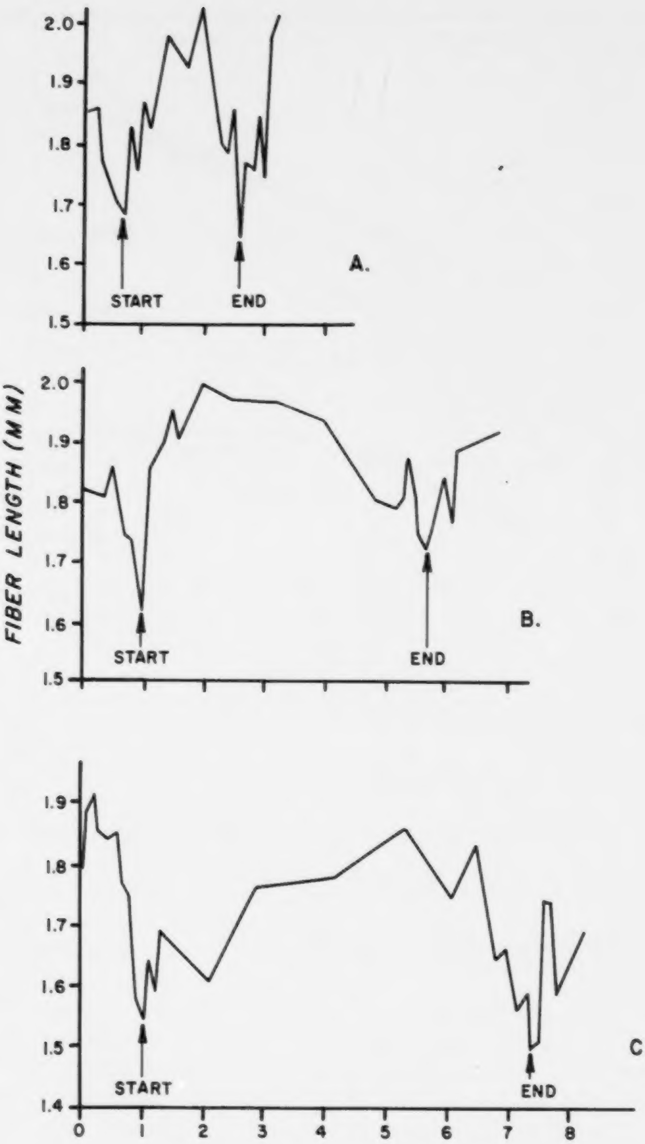

Figure 5-91.—Variation in fiber length across three separate rings of (A) Ring 24; (B) ring 9 of the same tree; and (C) ring 19 of another tree. (Drawing after Webb 1964, p. 131.)

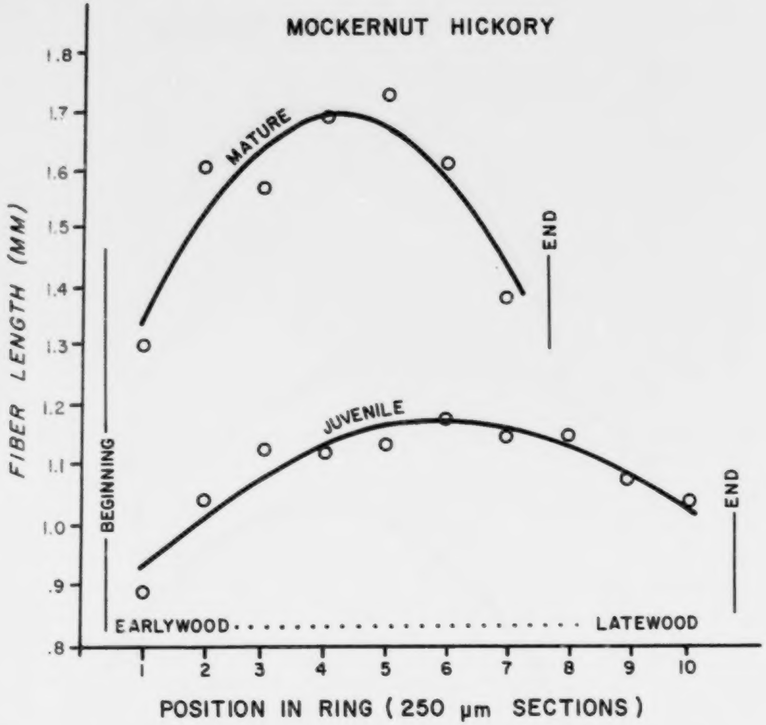

Figure 5-92.—Relationship of fiber length to position within rings of juvenile and mature wood of mockernut hickory. (Drawing after Taylor 1976.)

Stemwood vs branchwood.—F.G. Manwiller found that in 22 species of pine-site hardwoods, 6 inches in dbh sampled across their southern ranges, fiber length averaged 24.4 percent shorter in branches than in stems; branch means ranged from 20.5 percent shorter in red maple to 30.2 percent shorter in yellow-poplar (table 5-4).

Taylor (1977b) examined two 11-inch dbh trees of each of 8 species sampled at each of six mid-South locations (central Louisiana, central Arkansas, north and south Mississippi, and north and south Alabama); he also found that branchwood fibers were significantly shorter than stemwood fibers, as follows:

Species	Stemwood	Branchwood
	mm	
Hickory, mockernut	1.36	1.02
Hickory, shagbark	1.32	.93
Oak, post	1.37	.99
Oak, southern red	1.58	1.06
Oak, water	1.49	1.03
Sweetgum	1.78	1.12
Tupelo, black	1.93	1.28
Yellow-poplar	1.89	1.03

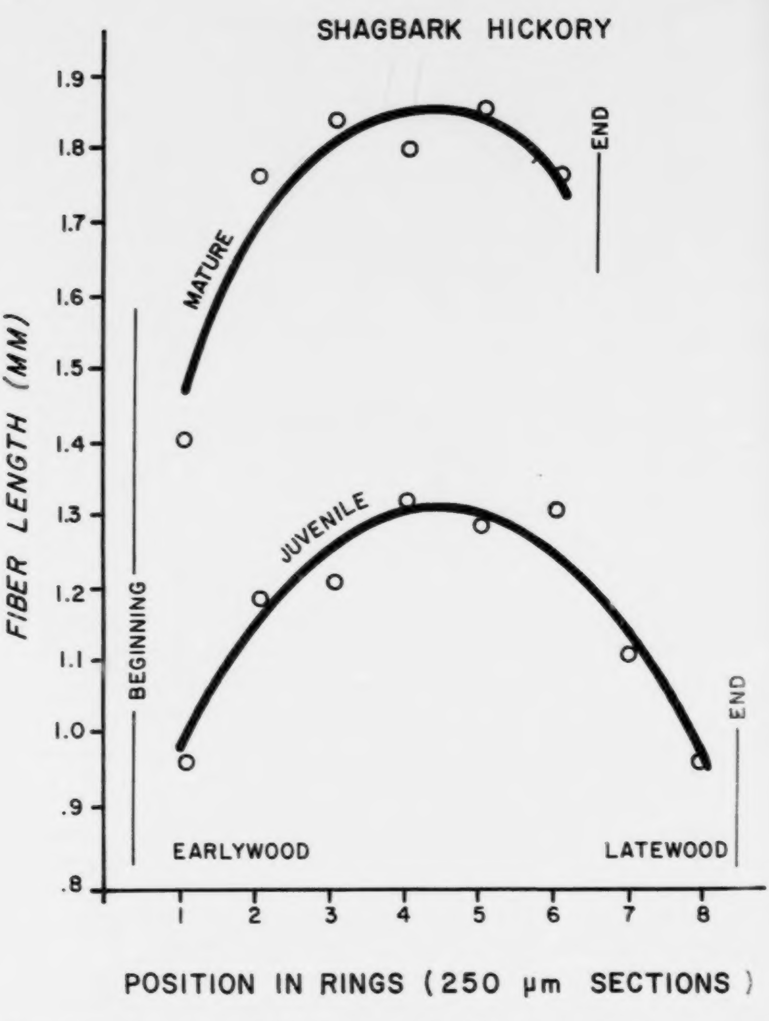

Figure 5-93.—Relationship of fiber length to position within rings of juvenile and mature wood of shagbark hickory. (Drawing after Taylor 1976.)

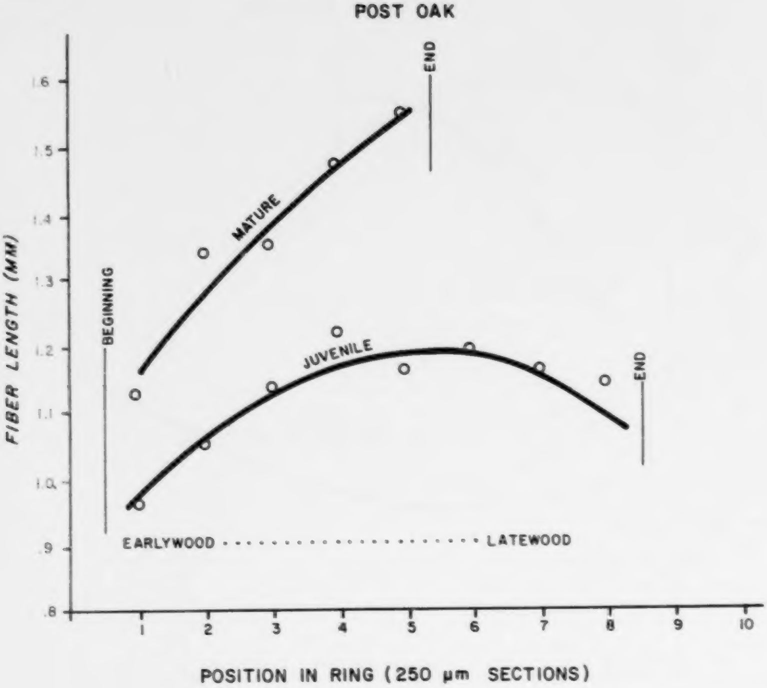

Figure 5-94.—Relationship of fiber length to position within rings of juvenile and mature wood of post oak (Drawing after Taylor 1976.)

Tree-average sampling.—From the foregoing paragraphs, it is evident that variation of fiber length within stems is substantial. Determinations of tree-average values by taking sequential stem sections and sampling proportionally by volume is a laborious and expensive procedure. Breast-height increment core samples, however, can be taken easily. Although data are not available for most of the hardwood species, it is likely that such breast-height samples or portions of samples, can be used to predict fiber-length averages for entire stems. Webb's (1964) study of sweetgum trees from the southeastern states concluded that fiber lengths measured across the entire width of the 20th annual ring at breast height provided a usable measure of tree-average fiber length; lengths measured in the fifth ring, however, were not significantly correlated with tree average values.

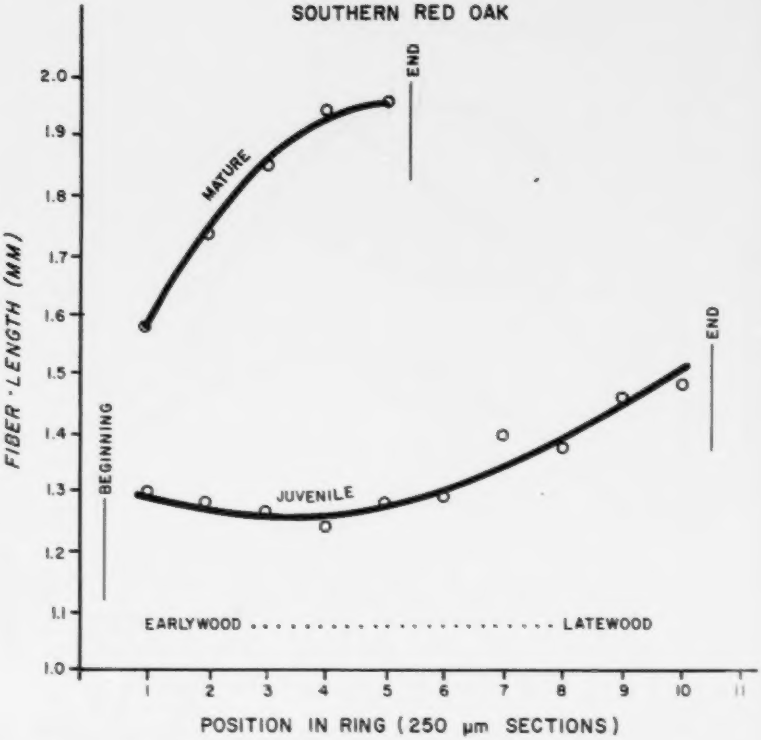

Figure 5-95.—Relationship of fiber length to position within rings of juvenile and mature wood of southern red oak. (Drawing after Taylor 1976.)

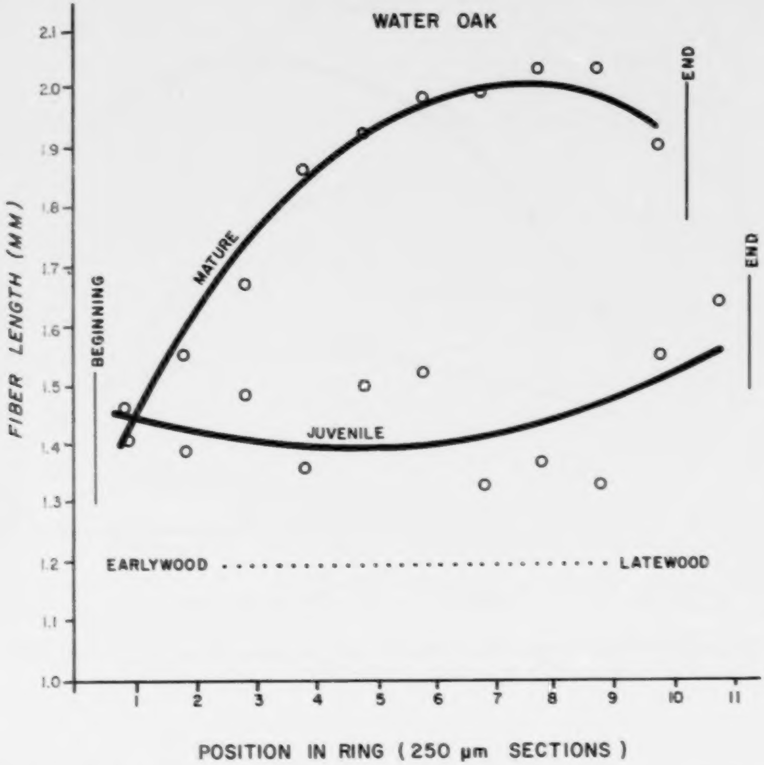

Figure 5-96.—Relationship of fiber length to position within rings of juvenile and mature wood of water oak. (Drawing after Taylor 1976.)

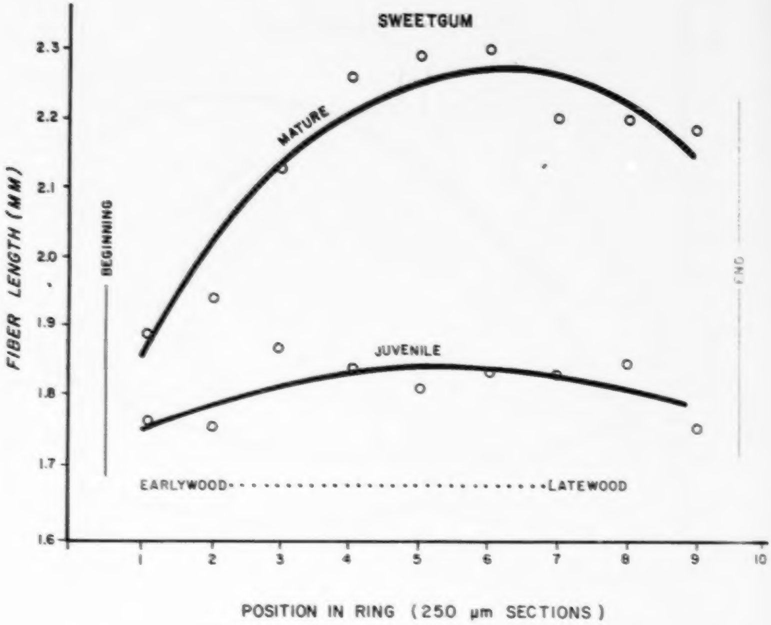

Figure 5-97.—Relationship of fiber length to position within rings of juvenile and mature wood of sweetgum. (Drawing after Taylor 1976.)

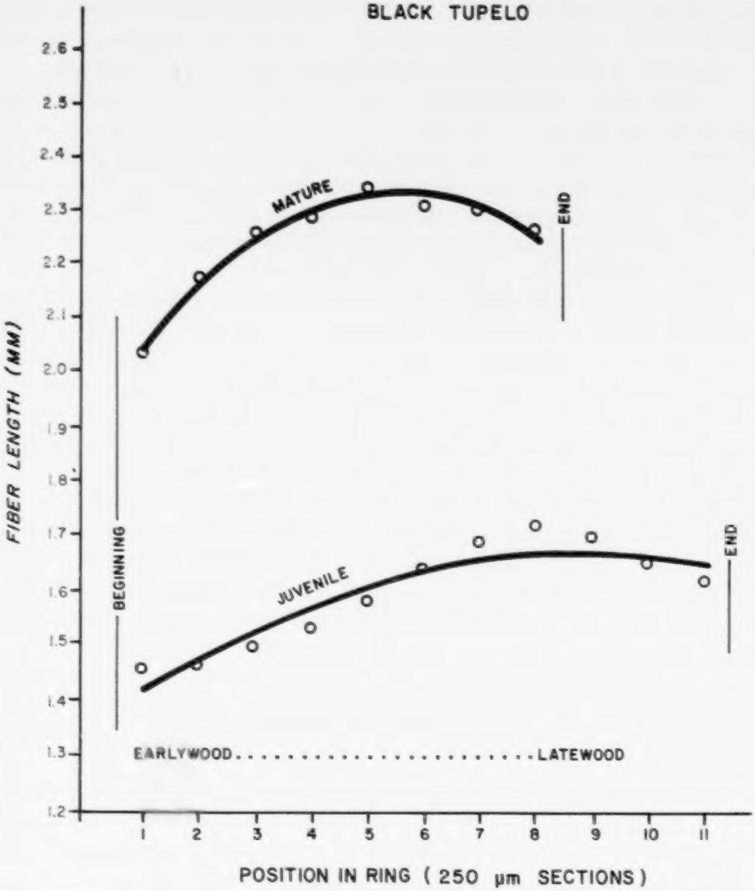

Figure 5-98.—Relationship of fiber length to position within rings of juvenile and mature wood of black tupelo. (Drawing after Taylor 1976.)

TRANSVERSE FIBER DIMENSIONS

Thickness of fiber walls has an effect on fiber conformability, and hence, on paper properties. For solid wood products, fiber-wall thickness and diameter are among the determinants of wood specific gravity and of mechanical properties.

To clarify the following discussion, **radial wall thickness** is the thickness of the radially aligned wall, and **radial fiber diameter** is the diameter measured in the radial direction; **tangential wall thickness** is the thickness of the tangentially aligned wall, and **tangential fiber diameter** is the diameter measured in the tangential direction.

Among-species variation.—Few published data giving species average values for transverse fiber dimensions are available. Manwiller's study (see table 5-7) of transverse dimensions in stems and branches of 22 species of small hardwoods on southern pine sites provides such data. His sampling procedure is described in the discussion related to table 5-4. Radial diameters and tangential wall thicknesses were measured with a traveling microscope on solid wood cross sections, and were weighted so that averages represented entire trees.

Manwiller's results are summarized in table 5-7, with species listed by decreasing fiber radial diameter. Stemwood fibers of sweetbay and yellow-poplar are the largest in radial diameter (27, 24 μm); winged elm and hackberry have fibers that are less than one-half as large (12, 11 μm). The ratio of fiber length to diameter, along with wall thickness, contribute to various pulping and paper characteristics (see tables 25-6 and 25-7 with related discussion).

Tangential wall thickness and lumen radial diameter of stemwood fibers parallel trends in fiber radial diameter with some variation. Black tupelo and sweetgum have the thickest walls and hackberry has a lumen radial diameter greater than the oaks.

Branchwood fiber dimensions are consistently smaller. Differences between fiber radial diameter in stemwood and branchwood range from 21 percent in yellow-poplar to 7 percent in winged and American elm. Tangential wall thickness and lumen radial diameter follow similar patterns.

Table 5-5 gives stem-average values for four species based on a larger collection of bigger trees.

Musha and Goring (1975) found fiber diameter and **double**-cell-wall thickness for sweetgum to be 21.3 and 10.9 μm, respectively, values that agree closely with those of Manwiller (table 5-7); Musha and Goring's dimensions are averages of both radial and tangential measurements made in transverse sections of earlywood.

Johnson and McElwee (1967) measured transverse dimensions in macerated sweetgum fibers from the 15th and 30th rings sampled at breast height in 140 trees drawn from the southern states from East Texas to North Carolina. Their values averaged as follows:

Annual ring	Fiber diameter	Wall thickness
	μm	
15	27.10	7.38
30	28.13	8.08

TABLE 5-7.—*Stemwood and branchwood fiber dimensions (transverse) in 6-inch-diameter hardwoods of 22 species grown on southern pine sites* (Data from Manwiller[1,2,3,4]

Species	Tree mean age	Fiber radial diameter		Tangential wall thickness		Lumen radial diameter	
		μm					
		STEMWOOD					
Sweetbay	39	26.98	(2.14)	4.81	(0.74)	17.36	(2.21)
Yellow-poplar	27	24.30	(1.51)	4.94	(0.59)	14.41	(2.41)
Sweetgum	29	22.84	(0.91)	5.99	(0.62)	10.86	(0.84)
Black tupelo	59	21.66	(1.97)	5.28	(0.62)	11.10	(1.12)
Red maple	40	18.02	(1.32)	3.19	(0.31)	11.63	(0.82)
White ash	40	17.75	(1.88)	4.12	(0.52)	9.51	(1.27)
Green ash	37	17.73	(2.20)	3.74	(0.61)	10.24	(1.81)
Laurel oak	33	15.48	(0.65)	4.54	(0.36)	6.40	(0.75)
Shumard Oak	34	15.47	(0.77)	4.69	(0.40)	6.08	(0.46)
Scarlet oak	33	15.45	(0.96)	4.77	(0.31)	5.91	(0.89)
Water oak	39	15.36	(0.72)	4.48	(0.29)	6.40	(0.53)
Blackjack oak	39	15.28	(0.91)	4.92	(0.31)	5.45	(0.60)
Cherrybark oak	32	15.21	(0.82)	4.61	(0.44)	6.00	(0.29)
Northern red oak	40	15.00	(0.28)	4.61	(0.26)	5.78	(0.55)
Southern red oak	35	14.98	(0.73)	4.68	(0.26)	5.62	(0.62)
Black oak	39	14.91	(0.76)	4.65	(0.23)	5.61	(0.59)
Hickory	54	14.77	(1.38)	4.02	(0.35)	6.74	(1.18)
White oak	41	14.51	(0.78)	4.58	(0.42)	5.35	(0.76)
American elm	40	14.27	(0.70)	4.17	(0.35)	5.94	(0.48)
Post oak	51	14.19	(0.72)	4.63	(0.40)	4.93	(0.90)
Hackberry	28	12.34	(0.94)	2.55	(0.30)	7.23	(0.70)
Winged elm	47	11.42	(0.65)	3.72	(0.23)	3.99	(0.56)
Average		16.72		4.44		7.84	

See footnotes at end of table

Table continued pg. 338

Within-species variation.—From Tables 5-5 and 5-7, it is evident that transverse fiber dimensions vary substantially among species, and among trees within species. A measure of this variation is given by the stemwood and branchwood columns listing within-species standard deviation in table 5-7. The Kellison-Zobel data (Table 5-5) also illustrate large among-tree variation; for example, young green ash trees have a range in radial fiber diameter from 14-26 μm and a range of tangential double-cell-wall thickness from 5-9 μm.

Within-tree variation.—Transverse fiber dimensions vary significantly with radial position in the stem, and with the height above ground; variation within annual ring is less pronounced.

In five 30-year-old yellow-poplar stems, analyzed along a radial transect 23 internodes below tree apex, Foulger et al. (1975) found that over a 22-year period, fiber and vessel radial diameters increased with increasing ring number from the pith (fig. 5-99); sometimes there was a positive correlation between ring width and cell diameter in individual years. Measurements were made on transverse sections with a traversing microscope.

TABLE 5-7.—*Stemwood and branchwood fiber dimensions (transverse) in 6-inch-diameter hardwoods of 22 species grown on southern pine sites* (Data from Manwiller[1,2,3,4])—continued.

Species	Tree mean age	Fiber radial diameter		Tangential wall thickness		Lumen radial diameter	
		μm					
		BRANCHWOOD					
Sweetbay	39	22.45	(1.16)	4.42	(0.61)	13.62	(1.94)
Yellow-poplar	27	19.17	(1.01)	3.81	(0.36)	11.55	(1.11)
Sweetgum	29	18.18	(0.48)	4.86	(0.35)	8.46	(0.86)
Black tupelo	59	17.95	(1.96)	4.44	(0.60)	9.06	(1.38)
Red maple	40	15.61	(1.11)	2.80	(0.32)	10.01	(0.64)
White ash	40	15.55	(1.61)	3.31	(0.41)	8.93	(0.96)
Green ash	37	15.58	(1.57)	3.14	(0.43)	9.29	(1.32)
Laurel oak	33	13.01	(0.70)	3.90	(0.24)	5.20	(0.72)
Shumard oak	34	12.82	(0.99)	3.76	(0.48)	5.31	(0.60)
Scarlet oak	33	12.47	(0.66)	3.79	(0.28)	4.89	(0.66)
Water oak	39	12.99	(0.63)	3.90	(0.30)	5.19	(0.37)
Blackjack oak	39	13.12	(0.62)	4.13	(0.25)	4.86	(0.55)
Cherrybark oak	32	12.35	(0.66)	3.71	(0.34)	4.92	(0.45)
Northern red oak	40	12.05	(0.90)	3.57	(0.42)	4.92	(0.46)
Southern red oak	35	12.53	(0.72)	3.88	(0.36)	4.76	(0.45)
Black oak	39	12.28	(0.94)	3.89	(0.25)	4.49	(0.54)
Hickory	54	13.07	(0.93)	3.27	(0.37)	6.53	(0.78)
White oak	41	12.06	(0.58)	3.71	(0.41)	4.65	(0.78)
American elm	40	13.33	(0.96)	3.60	(0.32)	6.13	(0.84)
Post oak	51	12.03	(0.74)	3.78	(0.46)	4.46	(1.18)
Hackberry	28	11.44	(0.99)	2.52	(0.37)	6.41	(0.54)
Winged elm	47	10.62	(0.57)	3.35	(0.27)	3.91	(0.53)
Average		14.12		3.71		6.71	

[1] Data in files of U.S. Dep. Agric. For. Serv., Study FS-SO-3201-1.42, Pineville, La.

[2] Averages based on a 10-tree sample of each species; sampling procedure yielded tree-average data for both stemwood and branchwood. Tree dimensions are given in tables 3-1 and 16-3.

[3] Species are listed in order of stemwood fiber diameter, from large to small.

[4] The first value tabulated under each heading is the average value; following (in parentheses) is the within-species standard deviation.

In a three-tree sample of green ash from Georgia, Saucier and Hamilton (1967) observed a sharp increase in fiber diameter (tangential, measured along a transect in the center of each annual ring) with number of rings from the pith (fig. 5-100). Similarly, radial fiber wall thickness in green ash increases with number of rings from the pith (fig. 5-101).

In a 78-foot white ash studied by Hiller (1968), earlywood had thinner tangential walls, but larger radial diameters than latewood fibers; at 26-foot height, fibers were slightly larger in diameter and had thicker walls than at 5 feet; transverse dimensions changed little with number of rings from the pith (table 5-8).

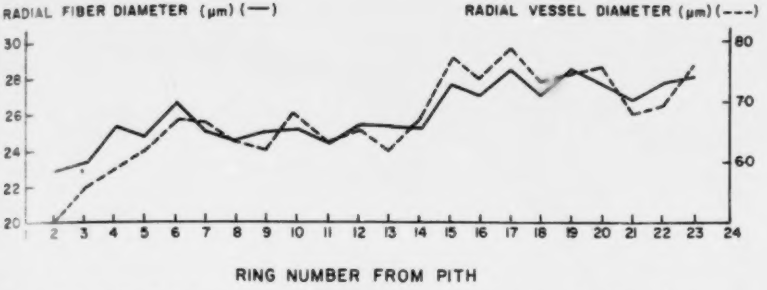

Figure 5-99.—Radial diameters of yellow-poplar fibers and vessels in radial sequence measured at the 23rd internode below stem apex. (Drawing after Foulger et al. 1975.)

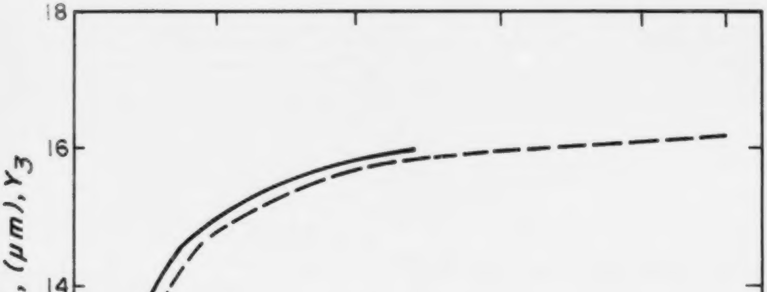

Figure 5-100.—Regression plot of tangential fiber diameter at two heights in a green ash stem related to rings from the pith. (Drawing after Saucier and Hamilton 1967.)

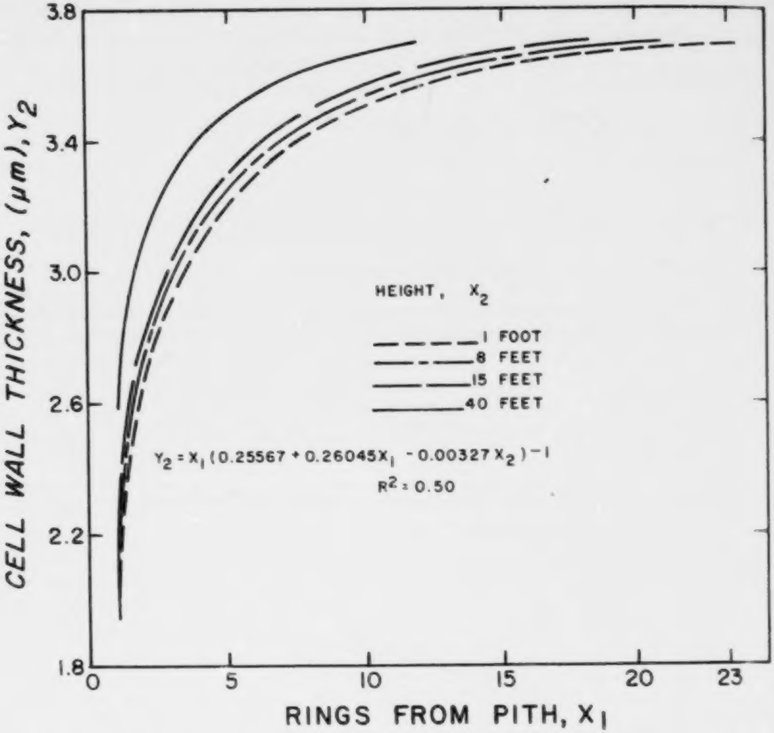

Figure 5-101.—Regression plot of radial fiber wall thickness in a green ash stem related to height in stem and rings from pith. (Drawing after Saucier and Hamilton 1967.)

Foulger et al. (1975) found that in yellow-poplar radial fiber diameter increases down an annual growth sheath, reaching a maximum and then decreasing slightly (fig. 5-102 right); for example, pooled data from the 1964 growth sheath showed a change from 21 μm at the 2nd internode below stem apex to a maximum of 29 μm in the 20th internode, and then to 28 μm in the 23rd internode. Maximum fiber diameters occurred in the lower stem, while the minimums were close to the pith at all heights (fig. 5-102 right).

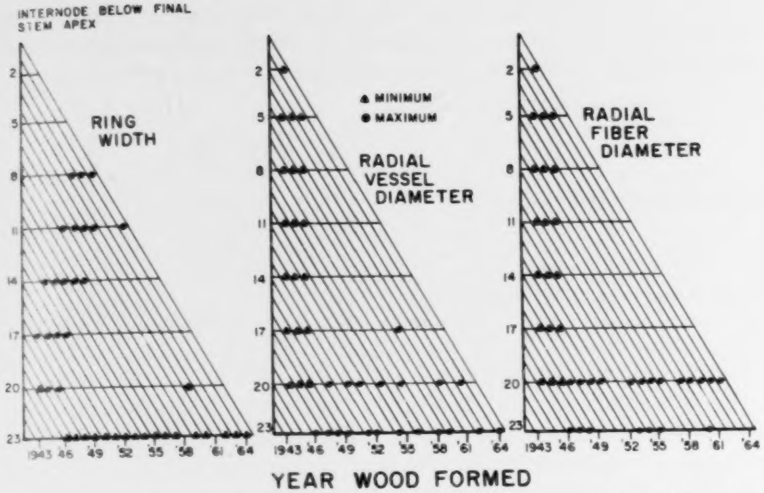

Figure 5-102.—Position of maximum and minimum in each annual growth sheath of yellow-poplar: (Left) Ring widths. (Middle) Radial vessel diameter. (Right) Radial fiber diameter. Two maxima or minima within a single sheath indicates identical values at two points in the sheath. Diagrams represent annual rings on a radial face exposed from the top of the tree down to the 23rd internode. (Drawing after Foulger et al. 1975.)

TABLE 5-8.—*Average transverse fiber dimensions in white ash earlywood and latewood at two heights and three radii (Hiller 1968)*

Types of tissue and number of rings from pith	Thickness of single fiber wall	Fiber lumen diameter	Fiber diameter
		µm	
		4.9 FEET ABOVE GROUND	
Earlywood			
16	2.9	10.0	15.8
26	3.1	10.8	17.1
36	3.0	10.4	16.5
Average	3.0	10.4	16.4
Latewood			
16	3.2	7.5	14.0
26	3.2	8.4	14.7
36	3.2	8.2	14.7
Average	3.2	8.1	14.5
		25.7 FEET ABOVE GROUND	
Earlywood			
6	3.3	9.4	16.0
16	3.1	10.5	16.8
26	3.1	12.3	18.5
Average	3.2	10.7	17.1
Latewood			
6	3.7	7.3	14.8
16	3.2	7.8	14.2
26	4.0	7.1	15.0
Average	3.6	7.4	14.7

In a study of 20 yellow-poplar trees from West Virginia, Yakub (1971) measured transverse sections at two heights in the tree; fibers had larger diameters and thinner walls at the 20-foot level than at ground level as follows:

Statistic and ring from pith	Height in tree	
	Ground level	20 feet
	μm	
Tangential fiber diameter		
1	21.64	24.70
2	21.85	22.09
3	21.75	22.18
Radial double-wall thickness		
1	9.59	6.93
2	9.88	8.36
3	10.07	8.64

Taylor's (1965) data for yellow-poplar confirm that weighted average fiber wall thickness decreases sharply from breast height to 20 feet, but thereafter increases with increasing height; fiber walls usually were thickest at the 60-foot sampling point. At lower stem sections, fiber wall thicknesses increased rapidly with increasing rings from the pith, leveling off beyond ring 20; at 60 feet there was virtually no increase in fiber wall thickness with increasing rings from the pith (Taylor 1965).

In green ash, Saucier and Hamilton (1967) also observed that fiber cell walls were thickest at upper stem levels (fig. 5-101).

Musha and Goring (1975) found that in Canadian hardwoods variation in transverse fiber dimensions within annual rings is minor except that the last few latewood cells in a ring usually have reduced radial diameter. In most cases, radial diameters of hardwood fibers were slightly greater than tangential diameters.

FIBRIL ANGLE IN FIBERS

Fibril angle as used in this discussion, refers to the average angle between fibrils in the S2 layer and the fiber longitudinal axis (fig. 5-103). Ash (and probably other hardwoods) with high fibril angles has less than normal strength—particularly stiffness (Pillow 1939); it may also have more than normal longitudinal shrinkage, although the evidence is not conclusive. Minute checks in the S2 layer—associated with high fibril angles—adversely affect tear and burst strength of sulfate and sulfite pulps (Pillow et al. 1941). For most purposes, therefore, wood with low fibril angles is preferable to wood with high angles.

Measurement of fibril angle.—The physical concept of fibril angle in the S2 layer of the secondary wall is well illustrated by electron micrographs (e.g., fig. 5-74, 5-104). Equipment for electron microscopy is too expensive, and techniques too exacting, for routine measurement of fibril angles. Four methods are in current use, two of them are applicable only to latewood.

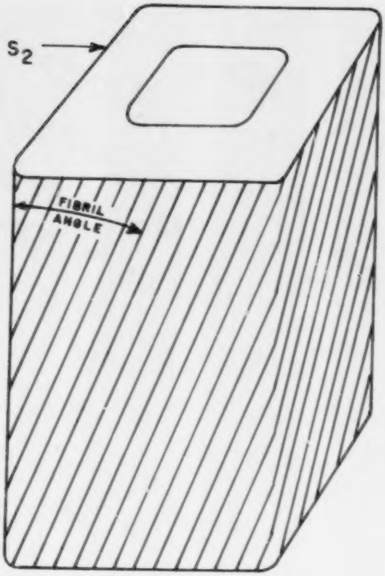

Figure 5-103.—Fibril angle in the S2 layer of the cell wall.

Marts (1955) described the fluorescence microscopy technique using heat to induce checks in latewood fibers. These checks, assumed parallel to the fibrils, are made visible on radial split sections with fluorochromes under ultraviolet light. Hiller and Brown (1967, p. 454) have described a procedure to improve its applicability to earlywood.

On latewood only, the inclination of apertures of bordered pits in longitudinal fibers (fig. 5-104) can be measured with a light microscope (Bailey and Vestal 1937; Wheeler and Thomas 1981).

A polarized light technique suitable for macerated fibers of both earlywood and latewood is described by Preston (1952, p. 116). Page (1969), Cousins (1972), and Leney (1981) described techniques applicable to intact fibers *in situ* and delignified or mounted single layers of cells.

Also applicable to both earlywood and latewood (*in situ*) is the X-ray diffraction technique described by Hermans (1949, p. 248).

The various methods do not yield identical data. Macerated fibers may shorten (and their fibril angles increase slightly) when released from the solid wood. Jurbergs (1963) compared the method of pit apertures with X-ray diffraction; his data on slash pine show a correlation coefficient of 0.766 between the two methods, with pit aperture angles slightly lower. McGinnes (1963, p. 19) found that in shortleaf pine estimates by the method of cell wall checks and polarized light agreed within a degree or two. The wall check method yielded slightly lower values. Manwiller found in spruce pine that the polarized light technique

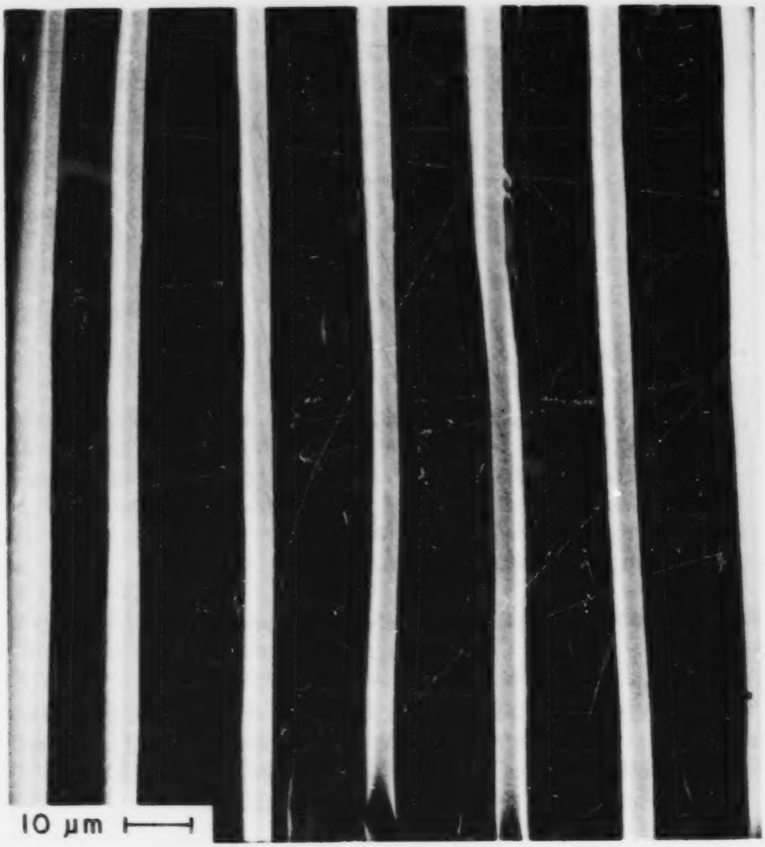

Figure 5-104.—Fibril angle. Bordered pits in face view on radial wall of fiber tracheids of yellow-poplar. Pits have canals and the long axes of slitlike inner apertures parallel microfibril alignment of the S2 layer. (Scanning electron charcoal micrograph from W.A. Côté.)

applied to macerated latewood tissues indicated fibril angles about 8° larger than those indicated by pit apertures observed in radial sections, and 4-5° larger fibril angles than the wall check method applied to macerated tissue.

Measurement technique should be specified in any comparative tabulation of fibril angles.

Among- and within-species variation.—There are insufficient published data to permit valid statistical comparisons of fibril angle among species or among trees within species. By Page's (1969) method, Horn (1978) measured the inclination of microfibrils in the S2 layer of fibers from five hardwoods, with results as follows: sweetgum—14.3°, American elm—15.5°, black tupelo—15.8°, shagbark hickory—19.4°, and white oak—13.7°. His samples were from 5-foot-long bolts from 5- to 10-foot height in each of two trees from each of two geographic locations.

Within-tree-variation.—In single trees of black and scarlet oak, McGinnes and Ralston (1967) found that juvenile wood has significantly larger fibril angles than mature wood, as follows:

Tissue location	90-year-old black oak	70-year-old scarlet oak
	Degrees	
Annual rings 1-10	10.0	15.2
Annual rings 11 and older	2.5	3.4

Samples were taken from the top of butt logs from each tree and fibril angle measured with polarized light technique (McGinnes 1963). Differences between the two species were not statistically significant.

In white and green ash, Pillow (1939) found that fibril angle decreases at heights above 8 to 12 feet and suggested that the large fibril angles at the base of the trunk are associated with low-density wood with comparatively thin fiber walls and large lumens.

Hiller (1968) intensively sampled a single 78-foot-high, 52-year-old white ash. Fibril angles were determined by measuring the deviation of elongated pit apertures from the longitudinal axis of the fiber under polarized light. No consistent radial trends were found in average fibril angles of growth rings taken at 5-ring intervals from pith to bark and at four heights in the tree; average fibril angle varied little over a span of 50 years.

Fibril angles decreased with height in tree; average fibril angle was less at heights above 8-12 feet than in the butt below these levels (fig. 5-105).

Fibril angles also varied across annual rings; earlywood had about 4-degree larger fibril angles than latewood, as follows (Hiller 1968):

Height in stem	Earlywood	Latewood
Feet	*Degrees*	
4.9	23.2	19.2
25.7	20.7	16.5

At all heights, fibril angle was negatively correlated with fiber length (r = −.44), i.e., long fibers had small fibril angles. Also, fibril angle decreased with increasing fiber wall thickness, as Pillow (1939) had suggested.

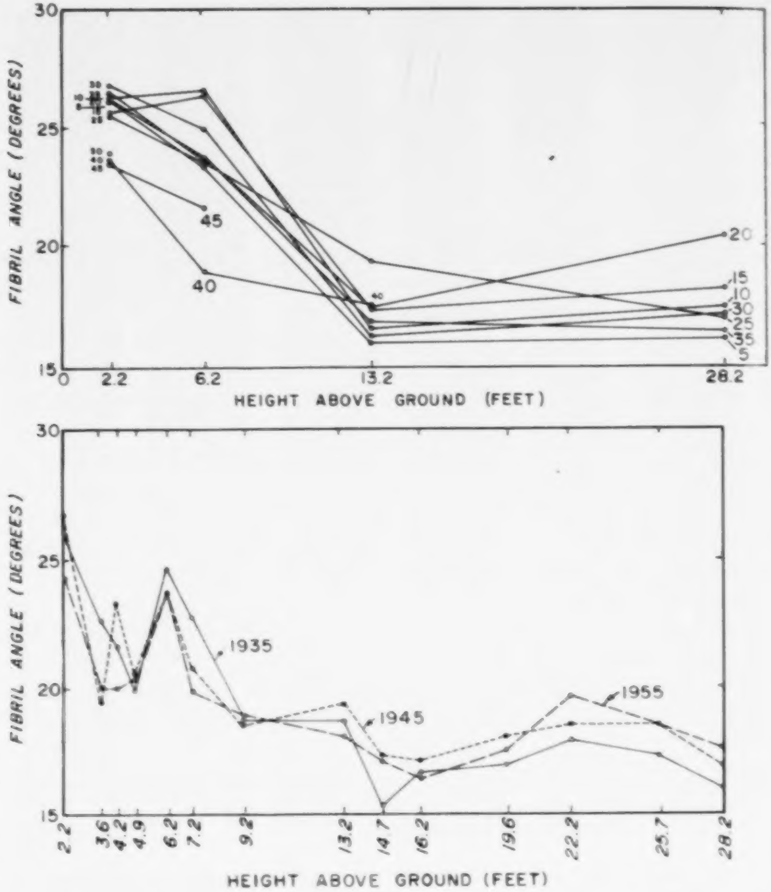

Figure 5-105.—Fibril angles in white ash. (Top) Average fibril angles in growth rings located at the same number of rings (5 to 45) from the pith related to height. (Bottom) Average fibril angles of growth rings formed in the same calendar year as related to height in stem. For all plots, each point represents the average fibril angle of an entire ring weighted by percentage of latewood. (Drawing after Hiller 1968.)

VESSEL ELEMENT LENGTH AND TRANSVERSE DIMENSIONS

Vessel size, tissue proportion, and distribution throughout the annual rings of hardwood strongly affect specific gravity, mechanical properties, and porosity of solid wood products. In general, vessel elements are shorter than fibers of their species.

The distribution of vessels within the annual ring varies among species (figs. 5-4 through 5-15 and 5-22 through 5-45), within species, and within individual trees (fig. 5-106). Section 5-9 discusses proportions of vessel tissue in the various species. The text in this subsection is limited to brief discussion of vessel length and transverse dimensions.

Among-species variation.—No data are presently available on tree-average vessel element lengths and diameters for 6-inch hardwoods on pine sites. Panshin and deZeeuw (1980) give average lengths and standard deviations for several of the species; among the longest are sweetgum and black tupelo at 1.32 mm and 1.33 mm respectively. American elm is shortest at .22 mm as follows (sampling procedure is not known):

	Vessel elements	
Species name	Average length	Standard deviation
	mm	
Ash, green	0.26	0.03
Ash, white	0.29	0.03
Elm, American	0.22	0.04
Hackberry	0.26	0.03
Hickory, mockernut	0.44	0.06
Maple, red	0.42	0.05
Oak, black	0.43	0.08
Oak, chestnut	0.40	0.09
Oak, northern red	0.42	0.09
Oak, post	0.43	0.09
Oak, scarlet	0.43	0.09
Oak, Shumard	0.45	0.08
Oak, white	0.40	0.09
Sweetgum	1.32	0.30
Tupelo, black	1.33	0.34
Yellow-poplar	0.89	0.13

Greenidge (1952) studied total vessel length (not vessel elements) in diffuse- and ring-porous hardwood trees including red maple, northern red oak, white ash, and American Elm. He concluded that a single vessel may extend from the secondary wood of the terminals to ground level and beyond in ring-porous species, while the length is determinate (e.g., 36 inches in red maple) in the less specialized diffuse-porous woods. He suggested that vertical rates of water conduction in large woody stems may be closely correlated with total vessel length. Burggraaf (1972) found that the vessels in the secondary xylem of *Fraxinus excelsior* L. were in contact over widely differing distances resulting in a loose three-dimensional vascular network.

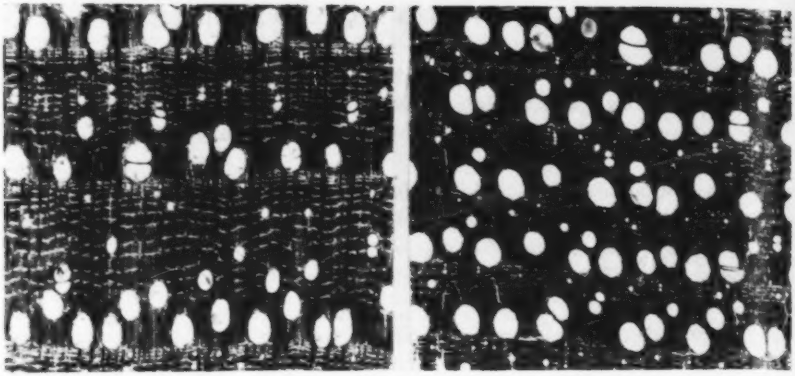

Figure 5-106.—Fast- (left) and slow-growth (right) hickory stemwood viewed in transverse section. Wide latewood is evident in section at left. 13X (Micrographs from W.A. Côté.)

Vessel diameter usually is measured in the tangential direction for consistency. In ring-porous species vessel diameter is several times larger in earlywood than in latewood; e.g., within a single growth ring of northern red oak, tangential diameters may exceed 240 μm in earlywood and be less than 40 μm in latewood. In diffuse porous woods vessel diameters are less varied and those in earlywood differ little from those in latewood. Earlywood vessels in sweetgum and black tupelo are 45-70 μm in diameter.

Length variation between and within trees.—In a study of breast-height increment cores taken from 240 dominant and codominant northern red oak sampled throughout the species range in the United States, Maeglin (1976) found that average vessel element length was 0.46 mm; individual vessel elements within trees had lengths from about 0.2 to 0.8 mm, and between geographic sites, site-average values for vessel length ranged from 0.38 to 0.53 mm.

Average vessel element length in a species is affected by environmental influences. For example, northern red oaks irrigated weekly with sewage effluent showed a 23 percent increase in earlywood vessel element length and a 12 percent increase in earlywood vessel element cell wall thickness (Young and Murphey 1972).

Radial variation within European ash was studied by Bosshard (1951), who found that the length of latewood vessel elements changes little with age; in contrast, earlywood vessel elements show an increase in length similar to that of fibers.

In shagbark hickory, the lengths of segments were found by Prichard and Bailey (1916) to increase from the pith outward (in a 60-year-old sprout, a 65-year-old seedling, and a 255-year-old tree) for at least the first 20 years, but then remained nearly constant during the later stages of tree development. In the same study of hickory, vessel segment length increased up the stem until a maximum was reached, and then decreased.

Transverse dimension variation between and within trees.—For purposes of identification, anatomists have adopted the following classification for vessel diameter measured in mature wood (Panshin and deZeeuw 1980):

Tangential diameter	Class designation
μm	
less than 50	Very small
51 to 100	Small
101 to 150	Medium
151 to 200	Large
201 to 300	Very large
more than 300	Extremely large

Such ring porous woods as elms and oaks have vessels classed as moderately large to very large; most of the other hardwoods have smaller vessels.

Vessel diameter variation among trees of a species is substantial. For example, average radial vessel diameter in earlywood of northern red oak may be less in slow-grown trees than in trees of average or fast growth, as follows (Maeglin 1974):

Tree growth rate	Radial diameter	Tangential diameter
	μm	
Slow	270	250
Average	330	240
Fast	325	240

In northern red oak, Zasada (1968) found that average radial diameter of vessels increased from 250 μm to 300 μm as site quality increased; no significant correlation was found between site index and tangential vessel diameter, however. In this study, earlywood width in the annual ring was positively correlated with vessel radial diameter measured in the outermost five rings of northern red oaks.

As noted earlier, vessel wall thickness in earlywood of northern red oak irrigated with sewage effluent increased 12 percent over the thickness observed in control trees (Young and Murphey 1972).

Within trees, variations in vessel diameter are substantial. In normal wood of a 22-year-old sweetgum sampled in the 17th to 19th ring, Musha and Goring (1975) noted the following averages and standard deviations in vessel dimensions:

Statistic	Average	Standard deviation
	μm	
Radial diameter	97	14
Tangential diameter	59	11
Wall thickness	1.9	0.3

In shagbark hickory, Prichard and Bailey (1916) found that vessel diameter increased radially throughout the life of even an old-growth tree, as follows:

Ring	Vessel diameter
years of age	µm
1	60
10	180
20-80	220
80-160	260
160-255	330

In a study of five yellow-poplars, Foulger et al. (1975) concluded that at any height in a stem, vessel radial diameter increased with the ring count from the pith, e.g., from 50µm at the second ring to nearly 80 µm at the 17th ring (fig. 5-99). In the same study, average vessel radial diameter increased rapidly down a growth sheath (e.g., from 42 µm at the 2nd internode to 76 µm at the 23rd internode). Thus, the continous columns (vessels) through which water is transported in yellow-poplar may be more nearly conical than cylindrical. Often there was reduction in vessel diameter at the lowest point in the sheath, although maximum vessel diameter usually occurred in the lowest two internodes (fig. 5-102 center) (Foulger et al. 1975).

Data comparing vessel characteristics of stem, root and branchwood of southern hardwoods are not at hand, and the literature on other hardwoods is sparse. Fegel (1941) found that both vessel diameter and vessel volume were greatest in the roots and least in the branches of the **diffuse-porous** hardwoods he studied. In **ring-porous** hardwoods, he found that vessel diameter was least in branches and vessel volume least in roots; stemwood vessels had greatest tangential diameter and volume. Fegel did not analyze differences between tap roots and lateral roots.

Patel (1965) studied five European species of hardwoods, comparing stemwood and rootwood (including both tap and lateral roots). He found ring-porousness was absent or not clearly defined in roots of species with ring-porous stemwood. Vessels were larger in rootwood (apart from earlywood zone) than in stemwood, but typical pore patterns were lacking; axial parenchyma were more abundant and rays were larger in roots. Esau (1965) stated that, compared with stemwood, rootwood may have larger vessels of more uniform size, sometimes fewer in number. For micrographs showing vessel patterns in rootwood of six pine-site hardwoods see figures 14-28 through 14-33.

5-11 KEYS TO IDENTIFYING HARDWOODS GROWING AMONG SOUTHERN PINES

Wood selected for identification should be mature, defect-free, with average growth rate. Inclusion of heartwood, if distinct in color, is useful. Wood is such a variable material that samples displaying very slow or very rapid growth may be difficult to identify. Comparison of unknown with known samples is helpful. Photographs at low magnification and in color (figs. 5-4 through 5-15) also are very useful. Since there are about 23 species of wood covered in this text, dichotomous keys are relatively easy to construct. Even so, certain woods cannot be identified as to species. For example, the oaks may be separated only as to red and white oak groups, on the basis of wood structure, using either gross or microscopic features. Identification of members of *Magnoliaceae* require the use of microscopic features, and the characteristics of the elms overlap to the extent that small samples may be mis-identified.

Two keys are presented. The first, based on macroscopic features, requires the use of a very sharp knife and a 10X hand lens. The second key, based on minute features, more accurately identifies species but requires preparation of temporary mounts, using a razor blade, and study with a compound microscope.

MACROSCOPIC KEY

1. Woods with two very distinct sizes of rays; extremely narrow and very broad. Broad rays seen easily as lines on the cross section; as ribbons or flecks on the radial and as distinct staggered broken lines on the tangential surface. Pores in groups or clusters that are radially oblique (dendritic) (Oaks) 2
1. Woods without extremely distinct sizes of rays. 3
    2. Latewood pores rounded, with thick walls and easily visible with hand lens. Pores usually somewhat sparse . . . . Red Oak, *Quercus* sp.
    2. Latewood pores angular, thin-walled, numerous, small and difficult to see with hand lens . . . . White Oak, *Quercus* sp.
3. Woods ring-porous or semi-ring porous. 4
3. Woods diffuse-porous 8
    4. Latewood pores arranged in wavy, tangential bands (ulmiform); the individual bands consisting of several rows of pores. Parenchyma not evident with hand lens 5
    4. Latewood pores not arranged as above; scattered more or less uniformly throughout the latewood, usually in multiples 7
5. Earlywood pores consisting of a single row, continuous or discontinuous. Rays barely visible to eye 6
5. Earlywood pores consisting of several rows. Rays distinct to eye. Wood clear yellow to greenish-yellow . . . . Hackberry, *Celtis* sp.
    6. Earlywood pores in a continuous, single row, wood moderately hard . . . . American elm, *Ulmus americana*
    6. Earlywood pores in a discontinuous, single row. Wood hard and heavy . . . . Winged elm, *Ulmus alata*

7. Apotracheal parenchyma visible as parallel, whitish lines in the latewood (wetted and with hand lens) .... True hickory, *Carya* sp.
7. Apotracheal parenchyma not evident. Paratracheal parenchyma visible with hand lens as encircling halos around latewood pores and as paratracheal-confluent parenchyma in the extreme outer latewood .... White, ash, *Fraxinus americana* .... Green ash, *Fraxinus pennsylvania*
    8. Growth rings distinct to eye; rays visible and appearing normally spaced occupying less than one-half of surface 9
    8. Growth rings indistinct to eye; rays fine and difficult to see without lens, closely spaced and appearing to make up about one-half of surface . 10
9. Pores uniformly and normally spaced, not appearing to occupy 50 percent of surface. Growth rings with marginal, brownish lines............. .... *Red maple, Acer rubrum*
9. Pores closely spaced except in outer margin of latewood; appearing to occupy more than 50 percent of surface. Growth rings distinct with whitish lines of parenchyma, easily visible when wood is wetted .... Yellow-poplar, *Liriodendron tulipifera* Sweetbay, *Magnolia virginia*.
    10. Wood on cross section appearing to consist of rays and pores, each appearing to occupy about 50 percent of surface. Pores uniformly spaced and frequently solitary .... Sweetgum, *Liquidambar styraciflua*.
    10. Rays appearing to occupy about 50 percent of surface. Pores often in radial lines or multiples separated by zones of mechanical tissue. Pore distribution lacking uniformity ...... Black tupelo, *Nyssa sylvatica*.

MICROSCOPIC KEY

1. Rays consisting of two very distinct sizes; extremely narrow (uniseriate) and very broad (50+ cells wide). Pores in groups or clusters that are radially oblique to the growth rings (dendritic) 2
1. Rays not consisting of two extremely distinct sizes. Pores not arranged as above 3
    2. Latewood pores angular, thin-walled, numerous and closely spaced. .... White oaks, *Quercus* sp.
    2. Latewood pores rounded, thick-walled, sparsely distributed in loose clusters. .... Red oaks, *Quercus* sp.
3. Wood ring-porous or semi-ring porous 4
3. Wood diffuse-porous 8
    4. Latewood pores arranged in wavy, tangential bands (ulmiform); the individal bands consisting of several rows of pores............ 5
    4. Latewood pores not arranged as above; scattered in a more or less uniform pattern throughout the latewood. Pores usually in multiples. Helical thickening absent 7

5. Earlywood pores consisting of several rows. Rays heterocellular; frequently exceeding 8 cells in width .... Hackberry, *Celtis* sp.

5. Earlywood pores consisting of a single continuous or interrupted row. Rays mostly homocellular, usually less than 8 cells in width 6

6. Earlywood pores in a single, continuous row.................. American elm, *Ulmus americana*.

6. Earlywood pores in a discontinuous, single row .... Winged elm, *Ulmus americana*

7. Apotracheal parenchyma present as continuous, short lines (banded) at right angles to the rays...................... True hickory, *Carya* sp.

7. Apotracheal parenchyma not evident. Paratracheal parenchyma visible as halos encircling latewood pores and pore multiples; paratracheal-confluent parenchyma frequent in extreme outer latewood ....
White ash, *Fraxinus americana*.
Green ash, *Fraxinus pennsylvanica*.

8. Vessel elements with simple perforations and helical thickening throughout. Rays homocellular .... Red maple, *Acer rubrum*.

8. Vessel elements with scalariform perforations. Rays heterocellular. Helical thickening, if present, restricted to tips of vessel elements . 9

9. Perforation bars usually 10 or less. Growth rings with several rows of marginal parenchyma.................................... 10

9. Perforation bars usually more than 20. Growth rings indistinct with flattened and thick-walled fibers at margin 11

10. Intervessel pitting uniformly opposite....................... Yellow-poplar, *Liriodendrom tulipifera*

10. Intervessel pitting scalariform and opposite. Linear pitting frequently interspersed with opposite pitting . . Sweetbay, *Magnolia virginiana*.

11. Intervessel pitting opposite, abundant and consisting of 4-6 rows ...... Black tupelo, *Nyssa sylvatica*.

11. Intervessel pitting opposite and scalariform, sparse and difficult to find Sweetgum, *Liquidambar styraciflua*.

5-12 LITERATURE CITED

Anonymous. 1937. Standard terms of length of vessel members and wood fibers. Trop. Woods No. 51, p. 21.

Anonymous. 1957. Tests for heartwood. *In* For. Prod. Res. 1956, p. 9. Dep. of Sci. and Ind. Res. London, Engl.: Her Majesty's Stationary Off.

Abeles, F.B., and G.R. Leather. 1971. Abscission control of cellulase secretion by ethylene. Planta 97:87-91.

Akins, V. and M.Y. Pillow. 1950. Occurrence of gelatinous fibers and their effect upon properties of hardwood species. Proc. For. Prod. Res. Soc. 4:254-264.

Anderson, A.B., T.C. Scheffer, and C.G. Duncan. 1963. The chemistry of decay resistance and its decrease with heartwood aging in incense cedar (*Libocedrus decurrens* Torrey). Holzforschung 17:1-5.

Arganbright, D.G. and D.W. Bensend. 1968. Relationship of gelatinous fiber development to tree lean in soft maple. Wood Sci. 1:37-39.

Bailey, L.F. 1948. Figured wood: a study of methods of production. J. of For. 46:119-125.

Bailey, I.W. and M.R. Vestal. 1937. Orientation of cellulose in the secondary wall of tracheary cells. J. Arnold Arbor. 18(3):185-195.

Baker, G. 1970. Some factors affecting the toughness of white ash. For. Prod. J. 20(8):51-52.

Barefoot, A.C., Jr. 1963. Abnormal wood in yellow-poplar (*Liriodendron tulipifera* L.) For. Prod. J. 13:16-22.

Basham, J.T. 1966. Heart rot of jack pine in Ontario. I. The occurrence of basidiomycetes and microfungi in defective and normal heartwood of living jack pine. Can. J. Bot. 44:275-295.

Bauch, J., W. Liese, and F. Scholz. 1968. Über die Entwicklung und stoffliche Zusammensetzung der Hoftüpfelmembranen von Langstracheiden in Coniferen. Holzforschung 22:144-153.

Beals, H.O. and T.C. Davis. 1973. An annotated bibliography of figure in wood. Agric. Exp. Stn. Circ. 205, 18 p. Auburn, Ala.: Auburn Univ.

Beals, H.O. and T.C. Davis. 1977. Figure in wood—an illustrated review. Agric. Exp. Stn. Bull. 486, 79 p. Auburn, Ala.: Auburn Univ.

Bergman, S.I. 1949. Lengths of hardwood fibers and vessel segments; a statistical analysis of forty-nine hardwoods indigenous to the United States. Tappi 32:494-498.

Berlyn, G.P. 1970. Ultrastructural and molecular concepts of cell-wall formation. Wood and Fiber 2:196-227.

Bissett, I.J. and H.E. Dadswell. 1949. The variation of fibre length within one tree of *Eucalyptus regnans*. F.v.M Aust. For. 13(2):86-96.

Bissett, I.J. and H.E. Dadswell. 1950. The variation in cell length within one growth ring of cerain angiosperms and gymnosperms. Aust. For. 14(1):17-29.

Bland, D.E., and W.E. Hillis. 1969. Microspectrophotometric investigation of lignin and polyphenol distribution in wood sections. Appita 23:204-210.

Bosshard, H.H. 1951. (Variation in the elements of ash wood as a function of cambial activity.) Schweizerische Zeitschrift fur Forstwesen 102(12):648-665.

Buchanan, W.D., F.G. Liming, and W. Harrison. 1962. Diameter growth patterns of black oak trees. J. of For. 60:342-343.

Burg, S.P. 1968. Ethylene, plant senescence and abscission. Plant Physiol. 43:1503-1511.

Burggraaf, P.D. 1972. Some observations on the course of the vessels in the wood of *Fraxinus excelsior* L. Acta Bot. Neerl. 21(1):32-47.

Burkart, L.F. and J. Cano-Capri. 1974. Tension wood in southern red oak *Quercus falcata* Michx. Tx. For. Pap. No. 25, 4 p. Stephen F. Austin State Univ., Nacogdoches, Tx.

Cano-Capri, J. and L.F. Burkart. 1974. Distribution of gelatinous fibers as related to lean in southern red oak (*Quercus falcata* Michx.). Wood Sci. 7:135-136.

Chafe, S.C. 1978. On the mechanisms of cell wall microfibrillar orientation. Wood Sci. and Technol. 12:203-217.

Chattaway, M.M. 1949. The development of tyloses and secretion of gum in heartwood formation. Aust. J. Sci. Res. B. 2:227-240.

Chattaway, M.M. 1952. The sapwood-heartwood transition. Australian For. 16(1):25-34.

Chow, P. 1961. Relation between fiber length and position in the bole of sweetgum. M.F. thesis. La. State Univ., Baton Rouge. 47 p.

Chow, P. 1971. Fiber length variation in the bole of an eccentric sweetgum tree. For Sci. 17(2):186-189.

Côté, W.A. 1967. Wood ultrastructure. An atlas of electron micrographs. 64 p. Univ. Washington Press, Seattle.

Cousins, W.J. 1972. Measurement of mean microfibril angles of wood tracheids. Wood Sci. and Technol. 6:58.

Dadswell, H.E. and J.W.P. Nicholls. 1959. Assessment of wood qualities for tree breeding. I. CSIRO Div. For. Prod. Tech. Pap. 4. 16 p.

Dadswell, H.E. and W.E. Hillis. 1962. Wood. *In* Wood extractives and their significance to the pulp and paper industries. (W.E. Hillis, ed.), p. 3-55. Academic Press, New York.

Davis, T.C. and H.O. Beals. 1977. Color in sweetgum wood. Agric. Exp. Stn. Circ. 231. 15 p. Auburn, Ala.: Auburn Univ.

Dietrichs, H.H. 1964. Physiologische Grundlagen der Holzverkernung. Mitteilungen der Bundesforschungsanstalt fuer Forst- und Holzwirtschaft 58:1-141. Reinbek.

Esau, K. 1965. Plant anatomy. John Wiley and Sons, New York. 2nd ed. 767 p.

Estes, E.T. 1970. Dendrochronology of black oak (*Quercus velutina* Lam.), white oak (*Quercus alba* L.), and shortleaf pine (*Pinus echinata* Mill.) in the Central Mississippi Valley. Ecol. Monogr. 40(3): 295-316.

Ezell, A.W., and P.E. Schilling. 1979. Within-tree variation of fiber length in sweetgum (*Liquidambar styraciflua* L.) in Louisiana. Wood Sci. 11:252-256.

Ezell, A.W., and J.L. Stewart. 1981. Variation of sweetgum fiber length within and between upland and bottomland sites. Wood and Fiber 13:246-251.

Farmer, R.E., Jr. 1969. Phenotypic variation in specific gravity and fiber length of cherrybark oak. Tappi 52:317-319.

Farmer, R.E., Jr. and W.L. Nance. 1969. Phenotypic variation in specific gravity and fiber length of cherrybark oak. Tappi 52:317-319.

Fegel, A.C. 1941. Comparative anatomy and varying physical properties of trunk, branch, and root wood in certain northeastern trees. NY State Coll. of For. Tech. Publ. No. 55, 20 p.

Fengel, D. 1970. Ultrastructure changes during aging of wood cells. Wood Sci. Technol. 4:176-188.

Foulger, A.N., F. Freese, and J. Harris. 1972. Effect of nutrient concentration on the stem anatomy of white ash seedlings. Wood and Fiber 4:112-114.

Foulger, A.N., J.P. Vimmerstedt, and C. Eichar. 1975. Stem anatomy of 30-year-old yellow-poplar. For Sci. 21(1):23-33.

Fraenkel, G.S. 1959. The raison d'etre of secondary plant substances. Sci. 129:1466-1470.

Franklin, E.C., M.A. Taras, and D.A. Volkman. 1970. Genetic gains in yields of oleoresin, wood extractives and tall oil. Tappi 53:2302-2304.

Frey-Wyssling, A. 1968. The ultrastructure of wood. Wood Sci. Technol. 2:73-83.

Fritts, H.C. 1959. The relation of radial growth to maximum and minimum temperatures in three tree species. Ecol. 40(2):261-265.

Fritts, H.C. 1962. The relation of growth ring widths in American beech and white oak to variations in climate. Tree-Ring Bull. 25(1-2):2-10.

Gerry, E. 1914. Tyloses: Their occurrence and practical significance in some American woods. J. Agric. Res. 1:445-470.

Goebel, N.B., M.A. Taras, and W.R. Smith. 1960. Tension wood and its relation to splitting in hickory. Bull. 480, Agric. Exp. Stn., Clemson Agric. Col., Clemson, S.C. 20 p.

Goto, T., H. Harada, and H. Saiki. 1978. Fine structure of cellulose microfibrils in poplar gelatinous layer and valonia. Wood Sci. and Technol. 12:223-231.

Greenidge, K.N.H. 1952. An approach to the study of vessel length in hardwood species. Amer. J. Bot. 39:570-574.

Hamilton, J.R. 1961. Variation of wood properties in southern red oak. For. Prod. J. 11:267-271.

Hamilton, J.R. and A.H. Chesser. 1969. Effects of acute ionizing radiation on the xylem fibers of *Quercus alba* and *Liquidambar styraciflua*. Radiat. Bot. 9:331-339.

Harada, H. 1964. Ultrastructure of angiosperm vessels and ray parenchyma. *In* Cellular ultrastructure of woody plants. (W.A. Côté, Jr., ed.), p. 235-249. Syracuse Univ. Press, Syracuse, N.Y.

Harlow, W.M., and E.S. Harrar, and F.M. White. 1979. Textbook of dendrology. 6th ed. McGraw-Hill Book Co., New York. 510 p.

Harper, H.J. 1961. Drought years in central Oklahoma from 1710 to 1959 calculated from annual rings of post oak trees. *In* Proc., Oklahoma Acad. Sci. 41:23-29.

Hart, J.H. and W.E. Hillis. 1972. Inhibition of wood-rotting fungi by ellagitannins in the heartwood of *Quercus alba*. Phytopathol. 62:620-626.

Hejnowicz, Z. and J.A. Romberger. 1973. Migrating cambial domains and the origin of wavy grain in xylem of broadleaved trees. Amer. J. Bot. 60(3):209-222.

Hemingway, R.W., and W.E. Hillis. 1970. Heartwood formation in living stumps of Douglas fir. Wood Sci. Technol. 4:246-254.

Hemingway, R.W., and W.E. Hillis. 1971. Changes in fats and resins of *Pinus radiata* associated with heartwood formation. Appita 24:439-443.

Hermans, P.H. 1949. Physics and chemistry of cellulose fibres. 534 p. New York, N.Y.: Elsevier Publ. Co., Inc.

Higuchi, T., M. Shimada, and K. Watanabe. 1967. Studies on the mechanism of heartwood formation. Pt. V. Change in the pattern of glucose metabolism in heartwood formation. J. Jap. Wood Res. Soc. 13:269-273.

Hiller, C.H. 1968. Trends of fibril angle variation in white ash. USDA For. Serv. Res. Pap. FPL 99, 8 p. For. Prod. Lab., Madison, Wis.

Hiller, C.H. and R.S. Brown. 1967. Comparison of dimensions and fibril angles of loblolly pine tracheids formed in wet or dry growing seasons. Am. J. Bot. 54(4):453-460.

Hillis, W.E. 1962. The distribution and formation of polyphenols within the tree. *In* Wood extractives and their significance to the pulp and paper industries. (W.E. Hillis, ed.), p. 59-131. Academic Press, New York.

Hillis, W.E. 1964. The formation of polyphenols in trees. II. The polyphenols of *Eucalyptus sieberiana* kino. Biochem. J. 92:516-521.

Hillis, W.E. 1966. Variation in polyphenol composition within species of *Eucalyptus* L'Herit. Phytochem. 5:541-556.

Hillis, W.E. 1968. Chemical aspects of heartwood formation. Wood Sci. Technol. 2:241-259.

Hillis, W.E. 1971. Distribution, properties, and formation of some wood extractives. Wood. Sci. Technol. 5:272-289

Hillis, W.E., and T. Inoue. 1966. The formation of polyphenols in trees. III. The effect of enzyme inhibitors. Phytochem. 5:483-490.

Hirai, S. 1951. [A study of the process of heartwood growth in the stem of Japanese larch.] Jap. For. Soc. Trans. 59:231-234

Höll, W. 1972. [Starch and enzymes of starch metabolism in the wood of *Robinia pseudoacacia*.] Holzforschung 26(2):41-45.

Horn, R.A. 1978. Morphology of pulp fibers from hardwoods. Res. Pap. FPL 312. U.S. Dep Agric., For Serv. 8 p.

Hugentabler, U.H. 1965. [Cytology of heartwood formation.] Vierteljahrsschift der Naturforschenden Gesellschaft in Zurich 110(2):321-342.

Hulme, A.C., M.J.C. Rhodes, and L.S.C. Wooltorton. 1971. The effects of ethylene on the respiration, ethylene production, RNA and protein synthesis for apples stored in low oxygen in air. Phytochem. 10:1315-1323.

Hunter, A.G. and J.F. Goggans. 1969. Variation of fiber length of sweetgum in Alabama. Tappi 52:1952-1954.

Hyodo, H., and S.F. Yang. 1971. Ethylene-enhanced synthesis of phenylalanine ammonia-lyase in pea seedlings. Plant Physiol. 47:765-770.

Imaseki, H. 1970. Induction of peroxidase activity by ethylene in sweet potato. Plant Physiol. 46:172-174.

International Association of Wood Anatomists, Committee on Nomenclature. 1964. Multilingual glossary of terms used in wood anatomy. International Association of Wood Anatomists, Zurich, Switzerland. 186 p

Jane, F.W. 1970. The structure of wood. (Rev. by K. Wilson and D.J.B. White) 2nd ed. 478 p. A. and C. Black, Ltd., London

Jensen, K.F. 1967. Measuring oxygen and carbon dioxide in red oak trees. U.S. Dep. Agric. For. Serv., Res. Note NE-74. 4 p.

Jett, J.B. and B.J. Zobel. 1975. Wood and pulping properties of young hardwoods. Tappi 58(1):92-96.

Johnson, J.W., and R.L. McElwee. 1967. Geographic variation in specific gravity and three fiber characteristics of sweetgum. Ninth South. Conf. For. Tree Improv. Proc., p. 50-55.

Johnson, F.L. and P.G. Risser. 1973. Correlation analysis of rainfall and annual ring index of central Oklahoma blackjack and post oak. Amer. J. Bot 60(5):475-478.

Jurbergs, K.A. 1963. Determining fiber length, fibrillar angle, and springwood-summerwood ratio in slash pine. For. Sci. 9:181-187.

Keith, C.T. 1977. A method for differentiating heartwood and sapwood in unseasoned timber. Bi-monthly Res. Notes 33(3):24-25. Can. For. Serv., Dept. Fish. and For.

Keller, R., P. Azoeuf, and R. Hoslin. 1974. (Tracer method for the measurement of spiral grain on standing trees.) Ann. Sci. For. 31(3):161-169.

Kishi, K., H. Harada, and H. Saiki. 1977. [Layered structure of the secondary wall in vessels of hardwoods by polarizing microscopy.] Bull. Kyoto Univ. For. 49:122-126. (Japan.)

Kishi, K., H. Harada, and H. Saiki. 1979. An electron microscopic study of the layered structure of the secondary wall in vessels. J. Jap. Wood Res. Soc. 25:521-527.

Kishi, K., H. Harada and H. Saiki. 1981. The structure of the primary wall of vessels in hardwoods. J. of the Society of Materials Science. Japan Vol. 30, No. 334, pp. 673-678.

Kollmann, F.F.P. and W.A. Côté, Jr. 1968. Principles of wood science and technology. I. Solid wood. 592 p. N.Y.: Springer-Verlag, New York Inc.

Kondo, T. 1964. [On the wood enzyme.] J. Jap. Wood Res. Soc. 10:43-48.

Koran, Z., and W.A. Côté, Jr. 1964. The ultrastructure of tyloses. *In* Cellular ultrastructure of woody plants. (W.A. Cote, Jr., ed.), p. 319-333. Syracuse Univ. Press, Syracuse, N.Y.

Krahmer, R.L., and W.A. Côté, Jr. 1963. Changes in coniferous wood cells associated with heartwood formatoin. Tappi 46:42-49.

Krahmer, R.L., R.W. Hemingway, and W.E. Hillis. 1970. The cellular distribution of lignans in *Tsuga heterophylla* wood. Wood Sci. Technol. 4:122-139.

Kumar, S. 1971. Causes of natural durability in timber. J. Timber Develop. Assoc. India 17(2):1-15.

Lairand, D.B. 1963. [The cytochemistry of wood elements.] Drev. Výskum 1963(1):1-11.

Lange, P.W. 1959. The morphology of hardwood fibers. Tappi 42:786-792.

Lassen, L.E. and G.A. Cooper. 1960. Significance of tension wood in furniture cuttings of red oak. U.S. Dep. Agric. For. Serv., FPL No. 2193. 12 p.

Leney, L. 1981. A technique for measuring fibril angle using polarized light. Wood and Fiber 13:13-16.

Lutz, J.F. 1972. Veneer species that grow in the United States. USDA For. Serv. Res. Pap. FPL 167, 127 p. For. Prod. Lab. Madison, Wis.

Lyr, H. 1962. [Enzymatic inactivation of heartwood toxins.] Flora, Jena 152:570-579.

MacDougal, D.T., J.B. Overton, and G.M. Smith. 1929. The hydrostatic-pneumetic system of certain trees: Movements of liquids and gases. Carnegie Institution of Washington Publ. No. 397. 99 p.

Maeglin, R.R. 1974. The effect of site quality and growth rate on the anatomy and utilization potential of northern red oak. *In* Whole tree utilization of hardwoods—an international meeting, proc. of the second annu. hardwood symp. of the Hardwood Res. Counc., pp. 191-205. Cashiers, N.C.

Maeglin, R.R. 1976. Natural variation of tissue proportions and vessel and fiber length in mature northern red oak. Silvae Genetica 25(3-4):122-126.

Manwiller, F.G. 1974. Fiber lengths in stems and branches of small hardwoods on southern pine sites. Wood Sci. 7:130-132.

Mapson, L.W., and A.C. Hulme. 1970. The biosynthesis, physiological effects and mode of action of ethylene. *In* Progress in Phytochemistry 2:343-384. (L. Reinhold and Y. Liwschitz, ed.) Interscience, New York.

Marei, N., and R. Romani. 1971. Ethylene-stimulated synthesis of ribosomes, ribonucleic acid, and protein in developing fig fruits. Plant Physiol. 48:806-808.

Marts, R.O. 1955. Fluorescence microscopy for measuring fibril angles in pine tracheids. Stain Technol. 30(5):243-248.

Matsukuma, N., H. Kawano, Y. Shibata, and T. Kondo. 1965. [Studies on the intermediate zone of sugi wood, some physiological activities of the xylem tissue.] J. Jap. Wood Res. Soc. 11:227-231.

McDougall, G.A. 1963. Radial growth studies. Can. Dep. of For. For. Entomol. and Pathol. Br. Bi-mon. Progr.Rep. 19(3):1.

McElwee, R.L., R.C. Tobias, and A.H. Gregory. 1970. Wood characteristics of three southern hardwood species and their relationship to pulping properties. Tappi 53:1882-1886.

McGinnes, E.A., Jr. 1963. Growth-quality evaluation of Missouri-grown shortleaf pine (*Pinus echinata*., Mill.) Univ. of Mo. Agric. Exp. Stn. Res. Bull. 841, 59 p.

McGinnes, E.A., Jr. and R.A. Ralston. 1967. Growth-quality evaluation of black and scarlet oak grown in Missouri. Agric. Exp. Stn. Res. Bull. 912, 15 p. Univ. of Mo., Coll. of Agric., Columbia, Mo.

McGinnes, E.A., Jr. and A.L. Shigo. 1975. A note on effects of wounds on heartwood formation in white oak (*Quercus alba* L.) Wood and Fiber 6:327-331.

McMillin, C.W., and F.G. Manwiller. 1980. The wood and bark of hardwoods growing on southern pine sites—A pictorial atlas. Gen. Tech. Rep. SO-29, U.S. Dep. Agric., For. Serv. 58 p.

Merrill, W. 1970. Spore germination and host penetration by heartrotting hymenomycetes. Ann. Rev. Phytopathol. 8:281-300.

Merrill, W., and E.B. Cowling. 1966. Role of nitrogen in wood deterioration: Amounts and distribution of nitrogen in tree stems. Can. J. Bot. 44:1555-1580.

Meyer, R.W. 1967. Tyloses development in white oak. For. Prod. J. 17(12):50-56.

Meylan, B.A., and B.G. Butterfield. 1978. Helical orientation of the microfibrils in tracheids, fibres, and vessels. Wood Sci. and Technol. 12:219-222.

Muhlethaler, K. 1964. The fine structure of the cellulose microfibril. *In* Cellular ultrastructure of woody plants. (W.A. Côte, Jr., ed.), p. 191-198. Syracuse Univ. Press, Syracuse, N.Y.

Murmanis, L. 1975. Formation of tyloses in felled *Quercus rubra* L. Wood Sci. 9:3-14.

Murmanis, L. 1976. The protective layer in xylem parenchyma cells of *Quercus rubra* L. Appl. Polym. Symp. No. 28:1283-1292.

Musha, Y. and D.A.I. Goring. 1975. Cell dimensions and their relationship to the chemical nature of the lignin from the wood of broad-leaved trees. Can. J. For. Res. 5:259-268.

Mutton, D.B. 1962. Wood resins. *In* Wood extractives and their significance to the pulp and paper industries. (W.E. Hillis, ed.), p. 331-363. Academic Press, New York.

Nelson, N.D., R.R. Maeglin and H.E. Wahlgren. 1969. Relationship of black walnut wood color to soil properties and site. Wood and Fiber 1:29-37.

Page, D.H. 1969. A method for determining the fibrillar angle in wood tracheids. J. Microscopy (Oxford) 90:137-143.

Panshin, A.J., and C. de Zeeuw. 1980. Textbook of wood technology. Structure, identification, properties, and uses of the commercial woods of the United States and Canada. 4th ed. 722 p. McGraw-Hill Book Company, New York.

Parham, R.A., K.W. Robinson, and J.C. Isebrands. 1977. Effects of tension wood on kraft paper from a short-rotation hardwood (*Populus "Tristis No. 1"*). Wood Sci. Technol. 11:291-303.

Parker, M.L., G.M. Barton, and J.H.G. Smith. 1976. Annual ring contrast enhancement without affecting X-ray densitometry surfaces. Tree-ring Bull. 36:29-31.

Patel, R.N. 1965. A comparison of the anatomy of the secondary xylem in roots and stems. Holzforschung 19:72-79.

Patterson, A.E. 1959. Distinguishing annual rings in diffuse porous tree species. J. of For. 57:126.

Paul, B.H. 1929. The relation of rate of growth to the production of white wood in hickory trees. South. Lumberman 137(1765):67.

Pillow, M.Y. 1939. Characteristics of ash from southern bottomlands. South. Lumberman 159(2009):131-136.

Pillow, M.Y., G.H. Chidester, and M.W. Bray. 1941. Effect of wood structure on properties of sulphate and sulphite pulps from loblolly pine. South. Pulp Pap. J. 4(7):6-12.

Preston, R.D. 1952. The molecular architecture of plant cell walls. 211 p. New York, N.Y.: John Wiley & Sons Inc.

Prichard, R.P., and I.W. Bailey. 1916. The significance of certain variations in the anatomical structure of wood. For. Quarterly T4(4):662-672.

Putnam, J.A. 1928. The occurrence of heartwood and figure in red gum. South. Lumberman 133(1734):204-206.

Randel, W.R. and J.E. Winstead. 1976. Environmental influence on cell and wood characters of *Liquidambar styraciflua* L. Bot. Gaz. 137(1):45-51.

Reid, M.S., and H.K. Pratt. 1972. Effects of ethylene on potato tuber respiration. Plant Physiol. 49:252-255.

Renton, J.J., M.J. Lanasa, and E.H. Tyron. 1974. Radiography for observing wood features. J. of For. 72:292-293.

Rhodes, M.J.C., and L.S.C. Wooltorton. 1971. The effect of ethylene on the respiration and on the activity of phenylalanine ammonia lyase in swede and parsnip root tissue. Phytochem. 10:1989-1997.

Ridge, I., and D.J. Osborne. 1970. Regulation of peroxidase activity by ethylene in *Pisum sativum*: Requirements for protein and RNA synthesis. J. Exp. Bot. 21:720-734.

Rudman, P. 1965. The causes of variations in the natural durability of wood: Inherent factors and aging and their effects on resistance to biological attack. Holz u. Organismen 1:151-62 Ed. G. Becker, W. Liese. Duncker & Humblot: Berlin.

Rudman, P. 1966. Heartwood formation in trees. Nature (London) 210:608-610.

Sachs, I.B., J.C. Ward, and E.H. Bulgrin. 1966. Heartwood stain in red oak. Holz als Roh- und Werkstoff 24:489-497.

Salem, M.H. 1961. Measurement and direction of eccentricity in the radial growth of straight boled post oak (*Quercus stellata* Wangenh.) trees. M.S. thesis. N.C. State Coll., Raleigh, N.C. 48 p.

Saucier, J.R. and J.R. Hamilton. 1967. Within-tree variation of fiber dimensions of green ash. Ga. For. Res. Pap. 45, 6 p.

Sachs, I., J. Kuntz, J. Ward, G. Nair, and N. Schultz. 1970. Tyloses structure. Wood and Fiber 2:259-268.

Saucier, J.R. and M.A. Taras. 1966. Specific gravity and fiber length variation within annual height increments of red maple. For. Prod. J. 16(2):33-36.

Scheffer, T.C., and E.B. Cowling. 1966. Natural resistance of wood to microbial deterioration. Ann. Rev. Phytopath. 4:147-170.

Shain, L., and J.F.G. Mackay. 1973. Phenol-oxidizing enzymes in the heartwood of *Pinus radiata*. For. Sci. 19:153-155.

Shigo, A.L. 1975. Heartwood and discolored wood. The North. Logger and Timber Proc. 24(2):28-29.

Shigo, A.L. and W.E. Hillis. 1973. Heartwood, discolored wood, and microorganisms in living trees. Annu. Rev. of Phytopathol. 11:197-222.

Shortle, W.S., A.L. Shigo, P. Berry, and J. Abusamra. 1977. Electrical resistance in tree cambium zone: Relationship to rates of growth and wound closure. For. Sci. 23:326-329.

Smith, W.J. 1967. The heritability of fibre characteristics and its application to wood quality improvement in forest trees. Silvae Genet. 16(2):41-50.

Smith, D.E. 1980. Abnormal wood formation following fall and spring injuries in black walnut. Wood Sci. 12:243-251.

Sorensen, R.W. and B.F. Wilson. 1964. The position of eccentric stem growth and tension wood in leaning red oak trees. Harvard For. Pap. No. 12. 10 p. Petersham, Mass.: Harvard Univ.

Stahmann, M.A., B.G. Clare, and W. Woodbury. 1966. Increased disease resistance and enzyme activity induced by ethylene and ethylene production by black rot infected sweet potato tissue. Plant Physiol. 41:1505-1512.

Stamm, A.J. 1977. Monomolecular adsorption and crystallite diameters of cellulose from structural and adsoprtion considerations. Wood Sci. and Technol. 11:39-49.

Stearns, J.L. and C. Hartley. 1952. Physicochemical methods for wood diagnosis. For. Prod. J. 2(4):58-61.

Stewart, C.M. 1966. Excretion and heartwood formation in living trees. Sci. 153:1068-1074.

Stutz, R.E. 1959. Control of brown stain in sugar pine with sodium azide. For. Prod. J. 9:459-463.

Taylor, F.W. 1963. Fiber length variation within growth rings of yellow-poplar (*Liriodendron tulipifera* L.) Tappi 46:578-581.

Taylor, F. 1965. A study of the natural variation of certain properties of the wood of yellow-poplar (*Liriodendron tulipifera*) within trees, between trees, and between geographic areas. Ph.D. thesis. N.C. State Univ., Raleigh, N.C. 190 p.

Taylor, F.W. 1968a. Specific gravity differences within and among yellow-poplar trees. For. Prod. J. 18(3):75-81.

Taylor, F.W. 1968b. Variations in the size and proportions of wood elements in yellow-poplar trees. Wood Sci. and Technol. 2:153-165.

Taylor, F.W. 1971. Variation of wood properties in sugarberry. For. Prod. Util. Lab. Res. Rep. No. 11, 17 p. State Coll., Miss.: Miss. State Univ.

Taylor, F.W. 1976. Fiber length variation within growth rings of certain angiosperms. Wood and Fiber 8(2):116-119.

Taylor, F.W. 1977a. Variation in specific gravity and fiber length of selected hardwoods throughout the Mid-South. For. Sci. 23:190-194.

Taylor, F.W. 1977b. A note on the relationship between branch- and stemwood properties of selected hardwoods growing in the Midsouth. Wood and Fiber 8:257-261.

Taylor, F.W. 1979. Property variation within stems of selected hardwoods growing in the Mid-South. Wood Sci. 11:193-199.

Thor, E. 1966. Improvement of yellow-poplar. *In* Proc. of the eighth south. conf. on for. tree improv., pp. 38-45. Macon, Ga.: Comm. on South. For. Tree Improv.

Thor, E., and H.A. Core. 1972. Relation of fertilization, irrigation and site factors with radial growth and wood properties of yellow-poplar. *In* Abst., Proc. Sixth TAPPI For. Biol. Conf., Inst. Pap. Chem., Appleton, Wis. Abst. V-1. 2 p.

Thorbjornsen, E. 1961. Variation in density and fiber length in wood of yellow- poplar. Tappi 44:192-195.

Trimble, G.R., Jr. 1969. Diameter growth of individual hardwood trees—the effect of certain tree environmental factors on the growth of several species. USDA For. Serv. Res. Pap. NE-145, 25 p. Northeast. For. Exp. Stn., Upper Darby, Pa.

U.S. Department of Agriculture, Forest Service. 1974. Wood handbook: Wood as an engineering material. U.S. Dep. Agric. For. Serv., Agric. Handb. 72, rev. For. Prod. Lab., Madison, Wis.

Vick, C.B. 1960. Tension wood. Coop. Publ. Ga. For. Comm. and U.S. For. Serv. Rel. No. 22, 4p.

Walters, C.S. 1970. Patridge wood: a novelty wood. For. Prod. J. 20(4):42.

Wardell, J.F. 1971. Formation of heartwood and discolored sapwood in white oak and white spruce. (Abstr.) Diss. Abstr. Int. B. Sci. Eng. 32(9):4971B-4972B.

Wardrop, A.B. 1962. Fundamental studies in wood and fibre structure relating to pulping processes. APPITA 16(3):15-30.

Wardrop, A.B., and J. Cronshaw. 1962. Formation of phenolic substances in the ray parenchyma of angiosperms. Nature (London) 193:90-92.

Webb, C.D. 1964. Natural variation in specific gravity, fiber length and interlocked grain of sweetgum (*Liquidambar styraciflua* L.) within trees, among trees, and among geographic areas in the South Atlantic States. Ph.D. thesis. N.C. State Univ., Raleigh. 125 p.

Webb, C.D. 1965. Variation in the wood of sweetgum. For. Farmer 24(12):9, 16-18.

Webb, C.D. 1969. Variation of interlocked grain in sweetgum. For. Prod. J. 19(2):45-48.

Wheeler, E.A. 1982. Ultrastructural characteristics of red maple (*Acer rubrum* L.) wood. Wood and Fiber 14:43-53.

Wheeler, E.A., and R.J. Thomas. 1981. Ultrastructural characteristics of mature wood of southern red oak (*Quercus falcata* Michx.) and white oak (*Quercus alba* L.). Wood and Fiber 13:169-181.

Womeldorff, F.M. 1965. Separation of heartwood from sapwood pulp chips by flotation methods. For. Prod. J. 15:407-408.

Wooten, T.E., T.W. Haene, and F.W. Taylor. 1973. Effect of tree release on wood quality of mature yellow-poplar trees. Wood Sci. 6:146-150.

Yakub, M. 1971. Variation in structure and specific gravity of yellow-poplar (*Liriodendron tulipifera* L.). Forestdale News 4(1):26-31.

Yazawa, K., and S. Ishida. 1965. [On the wet-heartwood of some broad-leaved trees grown in Japan. II. Seasonal moisture content of Yachi-damo and Haru-nire by months.] J. Fac. Agric. Hokkaido Univ. 54:123-136.

Yazawa, K., S. Ishida, and H. Miyajima. 1965. [On the wet-heartwood of some broad-leaved trees grown in Japan I.] J. Jap. Wood Res. Soc. 11:71-76.

Young, W.J., and W.K. Murphey. 1972. The effects of sewage effluent irrigation on various physical and anatomical characteristics of northern red oak. Res. Briefs 6(2):26-27.

Zasada, J.C. 1968. Earlywood in red oak: Vessel development and effect on site. (Abstr.) Diss. Abstr. 29B(3):831.

Zelawski, W. 1960. Respiration intensity of oak wood in particular annual rings of sapwood. Bull. de L'Academie Polonaise des Sciences, Serie des Sciences Biologiques 8:509-516.

Ziegler, H. 1963. Storage, mobilization, and distribution of reserve material in trees. *In* The formation of wood in forest trees. p. 303-320. (M.H. Zimmerman, ed.) Academic Press, New York.

Ziegler, H. 1967. Biological aspects of the heartwood formation. Holz als Roh-und Werkstoff 26:61-68.

Zobel, B.J. 1965. Inheritance of fibre characteristics and specific gravity in hardwoods—A review. *In* Proc., Meet. of Sec. 41, IUFRO, Vol. II, p. 1-14. (Melbourne, Vic.)

Zycha, H. 1948. [The formation of heartwood and allied processes in *Fagus sylvatica*.] Forstwiss. Cbl. 67(2):80-109.

6

Chemical constituents

In this chapter summative analytical data, and information on constituents of cellulose, hemicelluloses, and extractives were principally provided by H. L. Hergert, T. H. Sloan, J. P. Gray, and K. R. Sandberg.

Data characterizing lignin (sect. 6-5) are from R. D. Bleam and J. M. Harkin.

J. W. Rowe and A. H. Conner provided the information characterizing extractives.

Most of the quantitative data on extractives, ash, and mineral content were provided by F. G. Manwiller, as were the principal data on wood pH.

Other sources of information are cited in text and figures.

CHAPTER 6

Chemical constituents

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CHAPTER 6

Chemical constituents

Elements composing the organic portion of wood are carbon, hydrogen, and oxygen. Wood also contains small amounts of nitrogen and mineral elements; the latter remain as ash when wood is burned. The **ultimate analysis** of dry oak wood (*Quercus* sp.)—that is, the amount of the separate elements—was reported by Mitchell (1955) as follows:

Element	Sapwood	Heartwood
	Percent	
Carbon	49.2	50.3
Oxygen	44.2	43.6
Hydrogen	5.8	5.6
Nitrogen	.4	.3
Other inorganic elements, mostly metallic, found in ash	.4	.2

Percentages of these elements do not differ greatly among pine-site hardwood species.

The carbon, oxygen, and hydrogen are combined to form the organic polymer substances that make up the bulk of wood. These polymers are chemical substances of two main classes, carbohydrates and phenolics. The polymeric **carbohydrates,** also called **polysaccharides,** are made up of chains of sugar molecules. **Cellulose** and **hemicelluloses** comprise the polysaccharide portion of wood. Together they are called **holocellulose.** The polymeric phenolic portion of wood is, for the most part, a substance called **lignin.**

Cellulose is the principal component of the woody cell and makes up the framework of the cell wall. Surrounding and permeating this framework is a matrix of hemicellulose and lignin polymers. Lignin also occurs as an encrustant between cells.

In addition to the polymeric substances, wood also contains many components of low molecular weight (**extractives**) that are soluble in neutral organic solvents and water. As noted previously, it also contains small quantities of inorganic substances which remain as ash when wood is burned.

6-1 SUMMATIVE ANALYSIS

The chemical components of dry stemwood of pine-site hardwoods can be summed to 100 percent in **summative** or **proximate analysis**; the somewhat arbitrary percentages which follow are based on data from Hergert et al.[1] for upland hardwoods from eastern Tennessee.

		Percent (approximate)
Total polysaccharides, i.e., holocellulose		70.7
Cellulose	41.0 percent	
Hemicellulose	29.7 percent	
Lignin		24.4
Extractives		4.5
Ash		.4
		100.0

Hardwoods, including those on pine sites, have less lignin (about 24 percent) than softwoods (23 to 33 percent). Hardwood hemicellulose yields principally 5-carbon (**pentose**) sugars, mostly xylan; hemicellulose from softwood yields mostly 6-carbon (**hexose**) sugars.

Since the chemical pulp industry is based on removal of lignin and recovery of the cellulose from wood, it is useful to identify species with high cellulose and low lignin content. Southern hardwoods can also serve as raw material for production of chemicals other than cellulose. Furfural is one such chemical whose manufacture can be combined with chemical cellulose production by a two-stage process involving acid dehydration of the hardwood pentosans (Herrick and Hergert 1977). Hardwoods with greatest cellulose and pentosans content and least lignin and **resin** extractives soluble in petroleum ether should be candidates for this process.

Hergert et al.[1] have applied modern analytical methods such as chromatography and infrared spectroscopy to make summative analyses of 17 of the hardwoods that are the subject of this text (tables 6-1, 6-3, 6-5, and 6-7) plus 13 other southern hardwoods that occur in minor volumes on pine sites (tables 6-2, 6-4, 6-6, and 6-8), including determination of absolute content of cellulose. Bolts from trees 25 to 40 years old and 8 to 14 inches dbh were sampled in the vicinity of Jesup, (southeast) Georgia and Watts Bar, (eastern) Tennessee. Heartwood content did not exceed 5 percent of sample volume except in elms and oaks. (Heartwood generally contains nonextractable phenolic polymers which analyze as lignin by the Klason method.) The number of trees sampled per species at each location varied; unless otherwise specified in the tables, each value in tables 6-1 through 6-8 is based on several trees.

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[1] Hergert, H.L., T.H. Sloan, J.P. Gray, and K.R. Sandberg. The chemical composition of southeast hardwoods. Unpublished data privately communicated to the author December 12, 1977.

TABLE 6–1.—*Summative chemical analyses of principal hardwoods that grow on southern pine sites* (Hergert et al., see text footnote [1])

Species	Source[1]	Cellulose[2]	Hemi-cellulose[3]	Lignin[4]	Extractives[5]	Ash[6]
		Percent				
Ash, white	G	48.7	23.5	23.3	5.4	0.3
Ash, white[7]	T	39.5	29.1	24.8	6.3	.3
Elm, American[8]	G	42.6	26.9	27.8	1.9	.8
Elm, American[7]	G	38.0	32.5	24.7	4.6	.3
Elm, American[7]	T	41.9	29.7	25.6	2.4	.5
Hickory, mockernut	T	43.5	27.7	23.6	5.0	.4
Hickory sp.	G	37.7	29.2	23.0	9.0	1.1
Hickory, pignut	T	46.2	26.7	23.2	3.4	.6
Maple, red	G	39.9	28.2	23.0	8.6	.3
Maple, red	T	40.7	30.4	23.3	5.3	.3
Oak, black	T	39.6	28.4	25.3	6.3	.5
Oak, blackjack	T	33.8	28.2	30.1	6.6	1.3
Oak, chestnut	T	40.8	29.9	22.3	6.6	.4
Oak, northern red	T	42.2	33.1	20.2	4.4	.2
Oak, post	G	37.7	29.9	26.1	5.8	.5
Oak, post	—	40.3	28.6	25.4	5.1	.5
Oak, scarlet	T	43.2	29.2	20.9	6.6	.1
Oak, southern red	G	40.5	24.2	23.6	9.6	.5
Oak, southern red	—	43.9	27.6	23.0	5.2	.3
Oak, water	G	41.6	34.8	19.1	4.3	.3
Oak, white	G	43.7	24.2	24.3	5.4	1.0
Oak, white	T	41.7	28.4	24.6	5.3	.2
Sweetbay	G	44.2	37.7[10]	24.1	3.9	.2
Sweetgum[8]	G	42.8	30.1	25.7	1.1	.3
Sweetgum[9]	G	43.4	31.0	23.7	1.6	.3
Sweetgum	T	40.8	30.7	22.4	5.9	.2
Tupelo, black	G	44.9	23.2	28.9	2.6	.4
Tupelo, black	T	42.6	27.3	26.6	2.9	.6
Yellow-poplar	T	39.1	28.0	30.3	2.4	.3

[1] G indicates southeastern Georgia; T indicates eastern Tennessee. Except for species with footnotes 7, 8, and 9, number of trees in sample unknown.

[2] Computed from table 6-5 as 99 percent of glucan percentage minus half the mannan percentage. For example, cellulose percentage in sweetgum (G) = (44.5 − 2.4/2)(.99) = 42.8 percent, unextracted basis.

[3] Computed from table 6-3 as glucomannan plus acetylglucuronoxylan, plus arabinogalactan, plus pectin. For example, hemicellulose content in sweetgum (G) = 3.6 + 23.6 + 1.0 + 1.9 = 30.1 percent.

[4] Klason lignin, insoluble and soluble (by ultraviolet spectrum of filtrate, corrected for furfural and hydroxymethylfurfural).

[5] Extracted in succession with petroleum ether, ethyl ether or chloroform, 95-percent ethanol, and hot water. Total computed from table 6-7 as resin plus phenolics plus carbohydrates. For example, total extractives content in sweetgum (G) = 0.1 + 0.2 + 0.8 = 1.1 percent.

[6] Ashed at 575°C.

[7] Single tree; dimensions not recorded.

[8] 20 trees.

[9] Single tree, 7.1-in. diameter, 39 years old.

[10] Value in question; should perhaps be 27.7 percent.

TABLE 6–2.—*Summative chemical analyses of hardwoods that occur in minor volumes on southern pine sites* (Hergert et al., see text footnote[1])

Species	Source[1]	Cellulose[2]	Hemi-cellulose[3]	Lignin[4]	Extractives[5]	Ash[6]
		-----Percent-----				
Beech, American[7] (*Fagus grandifolia* Ehrh.)	T	36.0	29.4	30.9	3.4	0.4
Buckeye, yellow[7] (*Aesculus octandra* Marsh.)	T	40.6	25.8	30.0	3.1	.5
Cottonwood, eastern[8] (*Populus deltoides* Bartr.)	G	46.5	24.6	25.9	2.4	.6
Cottonwood, eastern[9]	G	47.0	25.0	26.0	1.6	.4
Dogwood, flowering[7] (*Cornus florida* L.)	T	36.8	35.4	21.8	4.6	.3
Loblolly-bay (*Gordonia lasianthus* (L.) Ellis)	G	43.8	29.1	21.5	5.2	.4
Oak, bear (*Quercus ilicifolia* Wangenh.)	G	37.6	27.5	26.4	8.0	.5
Oak, live (*Quercus virginia* Mill.)	G	38.1	22.9	25.3	13.2	.6
Pecan (*Carya illinoensis* (Wangenh.) K. Koch)	G	38.7	30.2	23.3	7.4	.4
Redbay (*Persia borbonia* (L.) Spreng.)	G	45.6	25.6	23.6	5.0	.2
Sassafrass[7] (*Sassafrass albidum* (Nutt.) Nees)	T	45.0	35.1	17.4	2.4	.2
Sourwood (*Oxydendrum arboreum* (L.) DC.)	T	40.7	34.6	20.8	3.6	.3
Sycamore[7] (*Platanus occidentalis* L.)	G	43.0	27.2	25.3	4.4	1
Tupelo, water (*Nyssa aquatica* L.)	G	45.9	24.0	25.1	4.7	.4

[1] G indicates southeastern Georgia; T indicates eastern Tennessee. Except for species with footnotes 7, 8, and 9, number of trees in sample unknown.

[2] Computed from table 6-6 as 99 percent of glucan percentage minus half the mannan percentage. For example, in table 6-5 cellulose percentage in sweetgum = (44.5 − 2.4/2)(.99) = 42.8 percent, unextracted basis.

[3] Computed from table 6-4 as glucomannan plus acetylglucuronoxylan, plus arabinogalactan, plus pectin. For example, in table 6-3 hemicellulose content in sweetgum = 3.6 + 23.6 + 1.0 + 1.9 = 30.1 percent.

[4] Klason lignin, insoluble and soluble (by ultraviolet spectrum of filtrate, corrected for furfural and hydroxymethylfurfural).

[5] Extracted in succession with petroleum ether, ethyl ether or chloroform, 95-percent ethanol, and hot water. Total computed from table 6-8 as resin plus phenolics plus carbohydrates. For example, in table 6-7, total extractives content in sweetgum = 0.1 + 0.2 + 0.8 = 1.1 percent.

[6] Ashed at 550°C.

[7] Single tree; dimensions not recorded.

[8] Two trees, 32 years old.

[9] Two trees, 46 years old.

TABLE 6–3.—*Components of hemicellulose in principal hardwoods that grow on southern pine sites* (Hergert et al., see text footnote[1])

Species	Source[1]	Gluco-mannan[2]	AGX[3]	Arabino-galactan[4]	Pectin[5]	Hem cel-lulos
		-------Percent of dry weight, unextracted basis-------				
Ash, white	G	1.9	16.4	1.7	2.4	23.5
Ash, white[7]	T	3.8	22.1	1.4	1.9	29.1
Elm, American[8]	G	4.6	19.9	.8	1.6	26.9
Elm, American[7]	G	5.3	24.6	1.0	1.6	32.5
Elm, American[7]	T	3.2	20.6	1.4	4.3	29.7
Hickory, mockernut	T	1.5	21.5	1.3	3.5	27.7
Hickory sp.	G	.8	24.9	1.8	1.7	29.2
Hickory, pignut	T	1.1	22.1	1.2	2.3	26.7
Maple, red	G	3.5	21.0	1.8	1.9	28.2
Maple, red	T	3.5	23.5	1.6	1.9	30.4
Oak, black	T	1.9	23.4	1.1	1.9	28.4
Oak, blackjack	T	2.0	21.0	2.3	2.9	28.2
Oak, chestnut	T	2.9	23.8	1.8	1.4	29.9
Oak, northern red	T	3.3	26.6	1.6	1.6	33.1
Oak, post	G	2.6	23.0	2.0	2.3	29.9
Oak, post	—	2.6	21.3	2.2	2.5	28.6
Oak, scarlet	T	2.3	23.3	1.4	2.2	29.2
Oak, southern red	G	1.7	18.6	1.7	2.2	24.2
Oak, southern red	—	1.8	21.9	2.0	2.0	27.6
Oak, water	G	3.0	28.9	2.2	.7	34.8
Oak, white	G	1.4	18.0	2.2	2.6	24.2
Oak, white	T	3.1	21.0	1.6	2.7	28.4
Sweetbay	G	4.3	20.2	1.6	1.6	37.7[10]
Sweetgum[8]	G	3.6	23.6	1.0	1.9	30.1
Sweetgum[9]	G	4.3	24.6	1.6	.5	31.0
Sweetgum	T	3.2	21.4	1.3	4.9	30.7
Tupelo, black	G	3.8	17.3	1.2	.9	23.2
Tupelo, black	T	3.6	18.0	1.0	4.8	27.3
Yellow-poplar	T	4.9	20.1	.7	2.4	28.0

[1] G means southeastern Georgia; T means eastern Tennessee. Except for species with footnotes 7, 8, and 9, number of trees in sample unknown.

[2] Glucomannan is the sum of mannan, from table 6-5, and glucan calculated as half the mannan For example, glucomannan in sweetgum = (2.4 + .5 X 2.4)(.99) = 3.6 percent, unextracted basis.

[3] Acetylglucuronoxylan is computed from table 6-5 as acetyl plus 4-0-methylglucuronan, which i calculated at 190/132 X 1/10 X corrected xylan, plus corrected xylan content. For example, AGX i sweetgum = 3.9 + .144 X 17.5 + 17.5 = 23.9 percent. This value multiplied by 0.99 = 23.6 percent, unextracted basis.

[4] Arabinogalactan is computed from table 6-5 as the sum of arabinan and galactan corrected f extractive content. For example, arabinogalactan in sweetgum = (0.4 + 0.6)(.99) = 1.0.

[5] Pectin is computed from total uronic acid from table 6-5 less calculated 4-0-methylglucuron associated with AGX from footnote[3] above. For example, pectin in sweetgum = (4.4 − .144 X 17.5)(.99) = 1.9 percent, unextracted basis.

[6] Hemicellulose content is approximated by the sum of glucomannan, AGX, arabinogalactan, an pectin. For example sweetgum hemicellulose content = 3.6 + 23.6 + 1.0 + 1.9 = 30.1 percent, unextracted basis.

[7] Single tree, dimensions not recorded.

[8] 20 trees.

[9] Single tree, 7.1-in. diameter, 39 years old.

[10] Value in question; should perhaps be 27.7 percent.

TABLE 6-4.—*Components of hemicellulose in hardwoods that occur in minor volumes on southern pine sites* (Hergert et al., see text footnote[1])

Species	Source[1]	Gluco-mannan[2]	AGX[3]	Arabino-galactan[4]	Pectin[5]	Hemi-cel-lulose[6]
		--------Percent of dry weight, unextracted basis--------				
Beech, American[8]	T	2.7	23.5	1.3	1.8	29.4
Buckeye, yellow[8]	T	3.6	18.6	1.0	2.6	25.8
Cottonwood, eastern[9]	G	4.4	16.8	1.6	1.8	24.6
Cottonwood, eastern[10]	G	5.0	18.4	.8	.8	25.0
Dogwood, flowering[8]	T	3.4	27.2	1.0	5.0	35.4
Loblolly-bay	G	4.1	22.1	1.1	1.8	29.1
Oak, bear	G	1.0	22.3	1.8	2.4	27.5
Oak, live	G	1.0	18.3	1.7	1.9	22.9
Pecan	G	1.6	24.7	1.6	2.3	30.2
Redbay	G	1.0	23.2	.9	.5	25.6
Sassafrass	T	4.0	30.4	.9	0.0	35.1
Sourwood[8]	T	1.3	31.9	1.0	.4	34.6
Sycamore[8]	G	2.3	22.3	1.4	1.2	27.2
Tupelo, water	G	3.5	18.6	.8	1.1	24.0

[1] See table 6-3 for botannical names of these species. Except for species with footnotes 8, 9, and 10, number of trees in sample unknown.

[2] G means southeastern Georgia; T means eastern Tennessee.

[3] Glucomannan is the sum of mannan, from table 6-6, and glucan calculated as half the mannan. For example, from table 6-5, glucomannan in sweetgum = (2.4 + .5 X 2.4)(.99) = 3.6 percent, unextracted basis.

[4] Acetylglucuronoxylan is computed from table 6-6 as acetyl plus 4-0-methylglucuronan, which is calculated at 190/132 X 1/10 X corrected xylan, plus corrected xylan content. For example, from table 6-5, AGX in sweetgum = 3.9 + .144 X 17.5 + 17.5 = 23.9 percent. This value multiplied by 0.99 = 23.6 percent, unextracted basis.

[5] Arabinogalactan is computed from table 6-6 as the sum of arabinan and galactan corrected for extractive content. For example, from table 6-5, arabinogalactan in sweetgum = (0.4 + 0.6)(.99) = 1.0 percent, unextracted basis.

[6] Pectin is computed from total uronic acid from table 6-6 less calculated 4-0-methylglucuronan associated with AGX from footnote[4] above. For example, from table 6-5 pectin in sweetgum = (4.4 − .144 X 17.5)(.99) = 1.9 percent, unextracted basis.

[7] Hemicellulose content is approximated by the sum of glucomannan, AGX, arabinogalactan, and pectin. For example, sweetgum hemicellulose content = 3.6 + 23.6 + 1.9 = 30.1 percent, unextracted basis.

[8] Single tree, dimensions not recorded.

[9] Two trees, 32 years old.

[10] Two trees, 46 years old.

TABLE 6–5.—*Constituents of cellulose and hemicelluloses of principal hardwoods that grow on southern pine sites* (Hergert et al., see text footnote[1])

Species	Source[1]	Uronic acid	Acetyl	Xylan[2]	Mannan[2]	Glucan[2]	Galactan[2]	Arabinan[2]
		Percent of dry weight, extractive-free basis						
Ash, white	G	4.3	2.9	12.6	1.3	52.9	0.7	1.1
Ash, white[3]	T	4.5	3.6	17.5	2.7	43.5	.6	.9
Elm, American[4]	G	4.4	3.8	14.6	3.2	45.9	.5	.4
Elm, American[3]	G	4.4	4.3	18.8	3.7	41.7	.6	.4
Elm, American[3]	T	6.6	4.0	15.0	2.2	44.1	1.0	.5
Hickory, mockernut	T	6.0	3.9	16.3	1.0	46.2	.9	.5
Hickory, sp.	G	4.9	3.1	21.3	.6	41.7	1.4	.6
Hickory, pignut	T	4.8	3.8	16.7	.8	48.2	.9	.4
Maple, red	G	4.3	5.2	15.6	2.6	44.9	1.1	.9
Maple, red	T	4.7	3.0	19.1	2.5	44.2	.9	.7
Oak, black	T	4.9	2.2	19.9	1.4	42.9	1.1	.9
Oak, blackjack	T	5.7	1.8	18.1	1.4	36.9	1.4	1.1
Oak, chestnut	T	4.2	3.8	18.9	2.1	44.8	1.2	.7
Oak, northern red	T	4.7	3.8	20.9	2.3	45.3	1.2	.5
Oak, post	G	5.1	3.3	18.4	1.9	40.9	1.3	.8
Oak, post	—	5.2	2.5	17.4	1.8	43.4	1.4	.9
Oak, scarlet	T	5.0	4.1	18.2	1.6	47.0	1.1	.4
Oak, southern red	G	4.6	3.1	15.3	1.2	47.3	1.2	.7
Oak, southern red	—	4.7	2.1	18.4	1.3	46.9	1.4	.8
Oak, water	G	3.9	4.6	22.4	2.1	44.5	1.6	.8
Oak, white	G	4.6	4.0	13.2	1.0	48.2	1.6	.7
Oak, white	T	5.2	3.7	16.1	2.2	45.1	1.1	.6
Sweetbay	G	4.0	2.7	16.0	3.0	47.4	1.1	.6
Sweetgum[4]	G	4.4	3.9	17.5	2.4	44.5	.6	.4
Sweetgum[5]	G	3.2	3.9	18.4	2.9	45.5	.5	1.2
Sweetgum	T	7.9	1.3	18.7	2.2	44.5	.9	.5
Tupelo, black	G	2.9	2.2	13.6	2.6	47.4	.2	.9
Tupelo, black	T	6.9	2.7	13.8	2.5	45.1	.6	.4
Yellow-poplar	T	4.6	3.1	15.3	3.3	41.7	.4	.3

[1] G means southeastern Georgia; T means eastern Tennessee. Except for species with footnotes 3, 4, and 5, number of trees in sample unknown.

[2] Carbohydrate content corrected for incomplete hydrolysis.

[3] Single tree, dimensions not recorded.

[4] Twenty trees.

[5] Single tree, 7.1-in. diameter, 39 years old.

TABLE 6–6.—*Constituents of cellulose and hemicelluloses of hardwoods that occur in minor volumes on southern pine sites* (Hergert et al., see text footnote [1])

Species[1]	Source[2]	Uronic acid	Acetyl	Xylan[3]	Mannan[3]	Glucan[3]	Galactan[3]	Arabinan[3]
		----------Percent of dry weight, extractive-free basis----------						
Beech, American[4]	T	4.7	2.2	19.4	1.8	38.2	.8	.6
Buckeye, yellow[4]	T	4.6	4.2	13.1	2.5	43.2	.5	.4
Cottonwood, eastern[5]	G	3.7	2.7	12.7	3.0	49.1	1.4	.2
Cottonwood, eastern[6]	G	2.8	2.9	13.8	3.4	49.5	.7	.1
Dogwood, flowering[4]	T	8.1	5.8	19.8	2.4	37.8	.8	.3
Loblolly-bay............	G	4.6	2.2	18.5	2.9	47.6	.7	.5
Oak, bear..............	G	4.9	6.1	15.9	.8	41.3	1.2	.8
Oak, live	G	4.1	5.6	13.6	.7	44.3	1.4	.6
Pecan	G	5.4	3.1	20.6	1.2	42.4	1.3	.4
Redbay	G	3.2	3.2	18.5	.7	48.4	.5	.4
Sassafrass..............	T	3.2	4.0	23.7	2.8	47.5	.6	.3
Sourwood[4]	T	3.9	5.6	24.0	.9	42.7	.7	.3
Sycamore[4]	G	3.7	3.6	17.3	1.6	45.8	1.1	.4
Tupelo, water............	G	3.3	2.2	15.1	2.5	49.4	.3	.5

[1] See table 6-2 for botanical names of these species. Except for species with footnotes 4, 5, and 6, number of trees in sample unknown.

[2] G means southeastern Georgia; T means eastern Tennessee.

[3] Carbohydrate content corrected for incomplete hydrolysis.

[4] Single tree, dimensions not recorded.

[5] Two trees, 32 years old.

[6] Two trees, 46 years old.

TABLE 6–7.—*Constituents of extractives of principal hardwoods that grow on southern pine sites* (Hergert et al., see text footnote[1])

Species	Source[1]	Resin[2]	Phenolics[3]	Carbo-[4] hydrates	Total[5] extractives
		Percent of unextracted dry weight			
Ash, white	G	0.2	4.0	1.2	5.4
Ash, white[6]	T	.7	3.3	2.3	6.3
Elm, American[7]	G	.3	.4	1.2	1.9
Elm, American[6]	G	.2	2.9	1.5	4.6
Elm, American[6]	T	.2	1.4	.8	2.4
Hickory, mockernut	T	.2	3.4	1.4	5.0
Hickory sp.	G	.4	6.0	2.6	9.0
Hickory, pignut	T	.2	1.8	1.3	3.4
Maple, red	G	.4	6.3	1.9	8.6
Maple, red	T	.8	3.0	1.5	5.3
Oak, black	T	.7	3.3	2.3	6.3
Oak, blackjack	T	.4	3.3	2.9	6.6
Oak, chestnut	T	.4	3.3	2.9	6.6
Oak, northern red	T	.4	2.6	1.4	4.4
Oak, post	G	.7	2.9	2.2	5.8
Oak, post	—	.6	2.1	2.4	5.1
Oak, scarlet	T	.6	4.2	1.8	6.6
Oak, southern red	G	.5	5.4	3.7	9.6
Oak, southern red	—	.5	3.0	1.7	5.2
Oak, water	G	.3	2.5	1.5	4.3
Oak, white	G	.4	3.4	1.6	5.4
Oak, white	T	.4	2.4	2.5	5.3
Sweetbay	G	.4	2.6	.9	3.9
Sweetgum[7]	G	.1	.2	.8	1.1
Sweetgum[8]	G	.3	1	1.2	1.6
Sweetgum	T	.5	3.7	1.7	5.9
Tupelo, black	G	.3	.1	2.2	2.6
Tupelo, black	T	.3	1.2	1.4	2.9
Yellow-poplar	T	.2	1.4	.8	2.4

[1] G mean southeastern Georgia; T means eastern Tennessee. Except for species with footnotes 6, 7, and 8, number of trees in sample unknown.

[2] Soluble in petroleum ether.

[3] Comprised of two fractions: (A) soluble in ether and insoluble in petroleum ether; (B) soluble in acetone and insoluble in ether.

[4] Soluble in water and insoluble in acetone.

[5] Sum of resin, phenolics, and carbohydrates.

[6] Single tree, dimensions not recorded.

[7] 20 trees.

[8] Single tree, 7.1-in. diameter, 39 years old.

TABLE 6–8.—*Constituents of extractives of hardwoods that grow in minor volumes on southern pine sites* (Hergert et al., see text footnote[1])

Species[1]	Source[2]	Resin[3]	Phenolics[4]	Carbo-[5] hydrates	Total extractives[6]
	-Percent -				
Beech, American[7].	T	.2	1.8	1.3	3.4
Buckeye, yellow[7]	T	.5	1.8	.8	3.1
Cottonwood, eastern[8]	G	.7	.5	1.2	2.4
Cottonwood, eastern[9].	G	.4	.4	.8	1.6
Dogwood, flowering[7].	T	.6	2.6	1.3	4.6
Loblolly-bay	G	.9	3.5	.8	5.2
Oak, bear	G	.7	5.6	1.7	8.0
Oak, live.	G	.5	10.5	2.2	13.2
Pecan	G	.5	5.4	1.5	7.4
Redbay	G	1.4	2.4	1.2	5.0
Sassafrass.	T	.2	1.3	.8	2.4
Sourwood[7].	T	.3	1.9	1.4	3.6
Sycamore[7].	G	.3	1.4	2.7	4.4
Tupelo, water	G	.3	.2	4.2	4.7

[1] See table 6-2 for botanical names of these species. Except for species with footnotes 7, 8, and 9, number of trees in sample unknown.

[2] G means southeastern Georgia; T means eastern Tennessee

[3] Soluble in petroleulm ether.

[4] Comprised of two fractions: (A) soluble in ether and insoluble in petroleum ether; (B) soluble in acetone and insoluble in ether.

[5] Soluble in water and insoluble in acetone.

[6] Sum of resin, phenolics, and carbohydrates.

[7] Single tree, dimensions not recorded.

[8] Two trees, 32 years old.

[9] Two trees, 46 years old.

Since analytical procedures affect summative data, the methodology of Hergert et al.[1] is abstracted to facilitate interpretation of tables 6-1 through 6-8. By their method, air-dry sawdust was extracted in succession with petroleum ether, ethyl ether (alternatively chloroform), 95-percent ethanol, and hot water. Extractive-free sawdust was submitted to the following analyses: (a) ash (550°C), (b) acetyl, (c) uronic acid anhydride (Bylund and Donetzhuber 1968), (d) Klason lignin, insoluble and soluble (by ultraviolet spectrum of filtrate, corrected for furfural and hydroxymethylfurfural), and (e) hydrolyzed sugars by paper chromatography. The procedure used in (e), (Jeffrey et al. 1960), does not result in the hydrolysis of aldobiuronic acids, so the xylan content was corrected by multiplying by 10/9 on the assumption that the average ratio of 4-0 methylglucuronic acid to xylose in hardwoods is 1:10. The molar ratio of glucose to mannose in glucomannan was assumed 1:2 (Timell 1960, 1964).

Hergert et al.[1] found that cellulose content of of hardwood species that grow on southern pine sites ranges from 33.8 percent of unextracted dry weight in blackjack oak to 48.7 percent in white ash from southeastern Georgia (tables 6-1 and 6-2). Of the hardwood species studied (tables 6-1, 6-2, 6-7, and 6-8), sweetgum, eastern cottonwood, sassafrass, and pignut hickory appeared most suitable for chemical cellulose production; i.e., these species have high cellulose content and low lignin and resin content. The Georgia sample of white ash—perhaps containing tension wood—had an outstandingly high cellulose content (48.7 percent) while the Tennessee sample was unusually low (39.5 percent.)

As previously noted in this section, among the more attractive proposals for making chemicals from wood are those that depend on a high xylan and cellulose content. These processes involve prehydrolysis and degradation of the xylan to form furfural followed by production of chemical cellulose from the residue, or hydrolysis of the cellulose followed by fermentation to yield ethanol. The species in the study of Hergert et al.[1] having large contents of both cellulose and xylan were sassafrass, sourwood, and some of the hickories and oaks. The latter are generally inferior for paper pulp production because of their vessel segments which give rise to "picking" during the printing process; for this reason they might be available for conversion to wood-based chemicals.

WITHIN-SPECIES AND WITHIN-TREE VARIATION

Analyses of trees within species show considerable variation, and differences are found between different parts of a single tree. Sapwood differs—in many cases quite appreciably—from heartwood (Hergert 1977), and earlywood may differ from latewood. Recognizing this, further studies are needed to determine if the high cellulose and xylan contents of some of the *Quercus* and *Carya* species, e.g., scarlet oak and pecan, are characteristics of the species or are dependent on site, age, or geographic location.

Davis (1973) found that the extractive content of northern red oak grown on limestone soils was significantly higher than that of trees grown on soils derived from sandstone. Cellulose content, however, did not differ with soil type. He reported that neither extractives content nor cellulose content of yellow-poplar wood was related to soil type. Thor and Core (1972) found that neither fertilization nor irrigation affected the extractives content of yellow-poplar.

The data presented in tables 6-1 and 6-2 were developed with advanced techniques available in 1978. Readers desiring to review earlier work on summative analyses of chemical constituents of hardwood species associated with southern pines will find the following references useful:

Species	Reference
Ash, white	Kellogg, et al. (1975) Mitchell (1955) Ritter and Fleck (1923, 1926 a,b)
Elm, American	Browning and Isenberg (1952) Clermont and Schwartz (1952) Lengyel (1964) Perem and Clermont (1962) Timell et al. (1958)
Hickory	Kellogg et al. (1975) McGovern et al. (1949) Mitchell (1955) Ritter and Fleck (1922, 1923)
Maple, red	Browning and Isenberg (1952) Kellog et al. (1975) Lengyel (1964) Timell (1965)
Oak, black	McGinnes and Ralston (1967)
Oak, blackjack	McGovern and Chidester (1948)
Oak, chestnut	Browning and Isenberg (1952)
Oak, northern red	David and Thompson (1964) Göhre and Wagenknecht (1955) Kellogg et al. (1975) Kubinsky and Ifju (1973 a,b) Ritter and Fleck (1926ab)
Oak, scarlet	McGinnes and Ralston (1967)
Oak, southern red	Wise and Ratliff (1947)
Oak species, southern	Schwartz (1958)
Oak, white	Kellogg et al. (1975) Ritter and Fleck (1923)
Tupelo, black	Wise and Pickard (1955)
Yellow-poplar	Kellogg et al. (1975)
Hardwoods in general	Smelstorius (1975)

Much of the data from these references is summarized in tabular form by Fengel and Grosser (1975). Hemingway (in press) summarized the literature on plant phenolic compounds.

6-2 DISTRIBUTION OF COMPOUNDS

Mature cell walls of hardwood fibers are complex layered structures (figs. 5-73 and 5-74). The intercellular substance, the true **middle lamella** which completely encloses individual cells and cements them to adjacent cells, is a continuous lignin-rich matrix. The thin outer layer of the cell wall which is difficult to distinguish from the middle lamella—i.e., the **primary wall**—is also highly lignified, but in addition contains hemicellulose, some cellulose, and pectin (plus protein). Together these layers are known as the **compound middle lamella.** The major portion of the cell wall, the **secondary wall,** is primarily cellulose and hemicellulose, but contains some lignin.

No data are available on lignin distribution across fiber walls of southern hardwoods, but Fergus and Goring (1970a,b) found that about 80 percent of the lignin in fibers of *Betula papyrifera* Marsh. is in the secondary wall layers; the rest is in the very thin middle lamella regions where it is a principal constituent. Fergus and Goring found that the secondary wall contains 16-19 percent lignin, the middle lamella 30-40 percent, and the cell corner regions 72-85 percent.

Timell (1967) found cellulose distribution in fibers of *Betula verrucosa*, as follows:

Cell layer	Cellulose portion of total polysaccharides in layer
	Percent
Middle lamella-primary wall	41
Secondary wall	48-60

Cellulose was found in highest concentration, and hemicelluloses in lowest, in wall regions nearest fiber lumens.

Wood rays of hardwoods, e.g., white oak, have appreciably greater lignin content and lower cellulose content than total stemwood (Harlow and Wise 1928). Tension wood (sect. 5-7 and figs. 5-71 and 5-72), on a gross weight basis, has less lignin and hemicellulose than normal wood, but more cellulose; per fiber, however, there is just as much lignin in tension wood as in a normal fiber (Timell 1969).

DISTRIBUTION WITHIN ANNUAL INCREMENTS

Ritter and Fleck (1926b) found that earlywood of white ash has more lignin and less cellulose than latewood. This is attributable to the fact that the middle lamella constitutes a greater proportion of total wood substance in earlywood than it does in latewood.

McGinnes and Wu (1973) and Wu and McGinnes (1974) have graphed such variation across growth increments of scarlet oak; also, they found that hemicellulose content was minimum in mid-increment, while extractives content was maximum in earlywood (fig. 6-1).

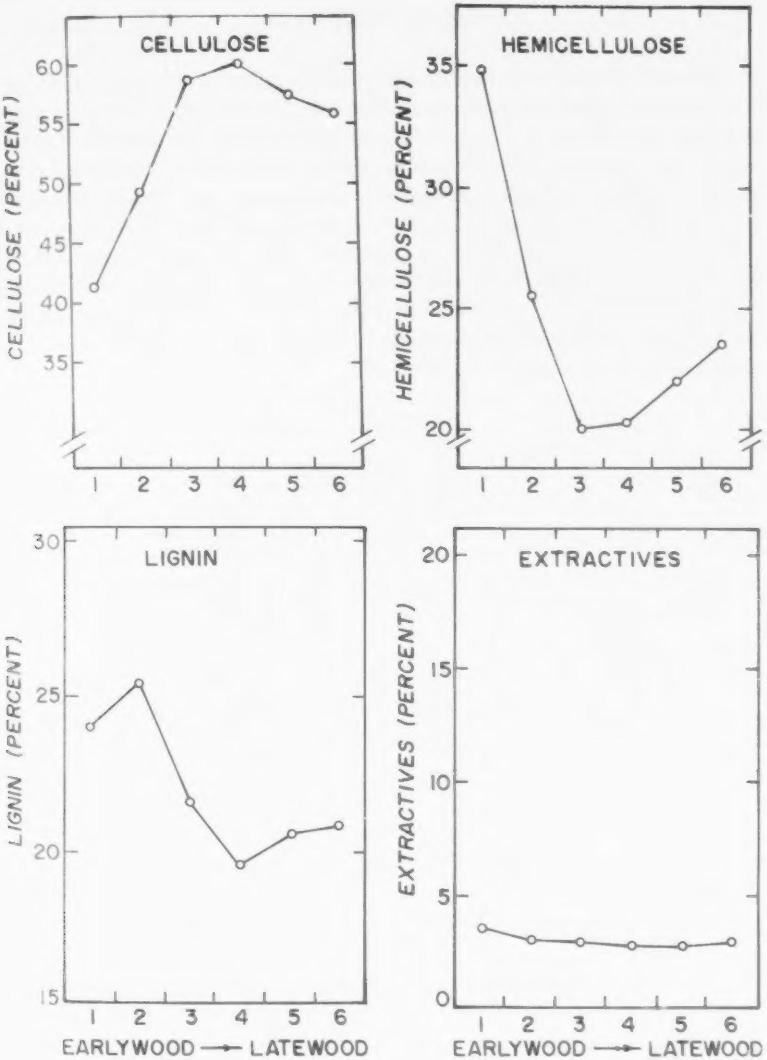

Figure 6-1.—Intra-incremental distribution of cellulose, hemicellulose, lignin, and extractives (extracted with ether, then ethanol, then water) in scarlet oak. Each increment is 1/6 of an annual ring. (Drawing after McGinnes and Wu 1973.)

6-3 CELLULOSE

Cellulose, like hemicellulose, is composed of sugars linked together through oxygen atoms into long slender-chain molecules. It differs from hemicellulose in that the molecules are about 10,000 sugar units long (Goring and Timell 1962) compared to a length of 150 to 200 units in hemicellulose molecules. The cellulose molecule is linear and comprised of glucose: hemicellulose molecules are branched and contain several kinds of sugars and sugar acids.

More technically, cellulose is a completely linear marcromolecule of D-glucose; the D-glucose is in pyranose ring form in the $4C_1$ chair formation (Sarko 1976). To date there is no conclusive evidence that cellulose in situ has a unique molecular weight as do many polymers, but some researchers believe it does. Its chemical structure is shown in figure 6-2.

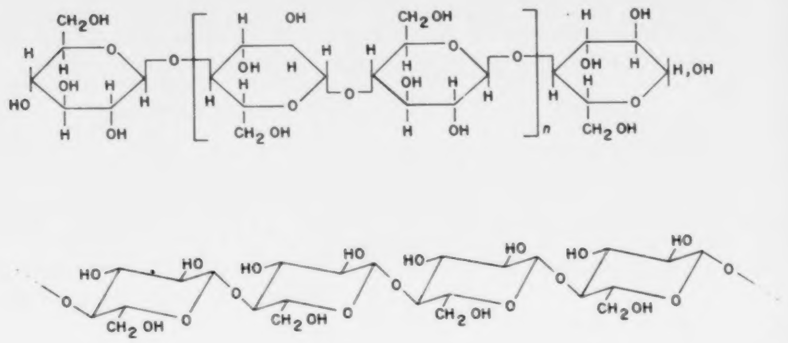

Figure 6-2.—Structural formula of cellulose. (Top) Constitution. (Bottom) Chair formation.

The cellulose molecules are linked laterally by hydrogen bonds into closely aligned linear bundles exhibiting crystallinity under X-ray analysis. The exact organization of cellulose molecules into **elementary fibrils** (cellulosic strands of the smallest possible diameter) and **microfibrils** (aggregations of elementary fibrils) is uncertain.

Sullivan and Sachs (1966), Cowling and Kirk (1976), and Mark (n.d.) have reviewed concepts of cellulose structure. Most investigators agree that additional research is needed to define the physical organization of cellulose in the cell walls of wood with certainty. For example, the dimensions of elementary fibrils may vary with species. Sullivan and Sachs (1966) found that elementary fibrils of northern red oak averaged 2.3 nm in diameter with range from 2.0 to 6.6. Hanna and Côté (1974) found diameters as small as 1.0 nm for some wood celluloses.

From observations of cellulose in gelatinous cell layers of *Populus euroamericana*, Goto et al. (1978) concluded that microfibrils in this species have a paracrystalline region surrounding a crystalline core and that the core is uniformly crystalline in the longitudinal direction, although there may be some crystalline dislocations. For further observations about orientation of cellulose crystallites in the S_2 layer of cell walls in *Betula* sp., see Revol et al. 1982.

Mark (n.d.) summarized the structure of wood (fig. 6-3) by noting that two of the major solid chemical constituents of wood, cellulose and hemicellulose, tend to be linear and tend to be aligned—the former strictly, the latter less so—with the microfibril axis. The third major solid constituent, lignin, is highly three-dimensional.

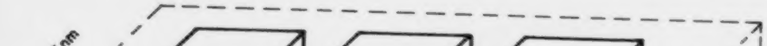

Figure 6-3.—Representative schematic view (dimensions are highly variable) of six cellulose microfibrils within a cell-wall space, viewed in cross section, of 43 x 12 nm. Short hemicellulose molecules occupy some of the space between microfibrils. Other substances (lignin, proteins, inorganic material, air, and water) occupy the remainder of the space. (Drawing after Mark n.d.)

6-4 HEMICELLULOSE

Hemicelluloses found in pine-site hardwoods are polymers comprised of chainlike, usually-branched, molecules containing 150 to 200 units of D-glucose, D-galactose, D-xylose, D-mannose, L-arabinose, and 4-0-methyl-D-glucuronic acid; these units are linked to one another by oxygen atoms. Hemicelluloses, along with lignin, surround the crystalline cellulose. From work on white birch fibers (*Betula papyrifera* Marsh.), Kerr and Goring (1977) concluded that much of the hemicellulose in fiber walls is arranged in tangential layers concentric with the cell axis.

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Hemicelluloses are usually soluble in cold aqueous alkali. In a mineral acid-water solution, the glycosidic linkages between sugars and sugar acids in hemicelluloses are broken and the sugars and sugar acids are separated; this process is termed **hydrolysis.** Hydrolyzed hemicelluloses from hardwoods yield principally two pentose sugars, mostly xylose (with a low percentage of arabinose) and about 10 percent of glucose together with small percentages of galactose and acids of glucose and galactose. Acid-hydrolyzed hemicelluloses also yield some acetic acid (Ritter 1951).

Hergert et al.[1] have measured hemicellulose content (23.2 to 35.4 percent of dry weight) and determined the components of hemicelluloses in hardwoods found on southern pine sites. In these analyses (tables 6-3 and 6-4, the acetylglucuronoxylan component was largest, followed by arbinogalactan, pectin, and glucomannan, as follows:

Component	Percent of total hemicellulose	
	Range	Tennessee average
Acetylglucuronoxylan	68.3 to 92.2	77.2
Glucomannan	2.7 to 20.0	9.4
Pectin	0 to 17.6	8.7
Arabinogalactan	2.5 to 9.1	4.7
Total hemicellulose content	100.0	100.0

Acetylglucuronoxylan has been found in every hardwood so far investigated. More precisely, the structural framework consists of (1- 4)-linked β-D-xylopyranose residues, some of which carry a 4-0-methyl-α-D-glucuronic acid residue linked directly to the 2-position. Seven out of ten xylose units are also acetylated, mostly at C-3, but to a certain extent also at C-2 (fig. 6-4). Most hardwoods in the temperature zone contain a xylan with ten xylose residues per acid side chain; an exception among southern hardwoods is American elm which has one acid group per six or seven xylose residues. The acid side chains are probably distributed at random along the xylan framework which contains 150 to 200 xylose residues per average molecule (Timell 1965).

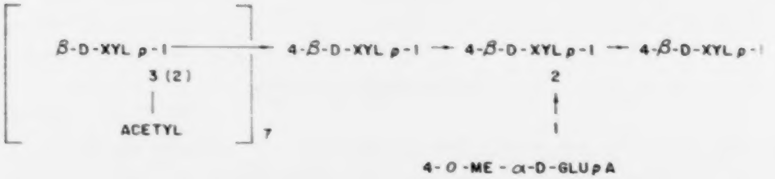


Figure 6-4.—Repeating unit of *O*-acetyl-4-*O* methylglucurono-xylan. Xyl means xylose, Me means methyl, and Glu means glucose. (Drawing after Timell 1965.)

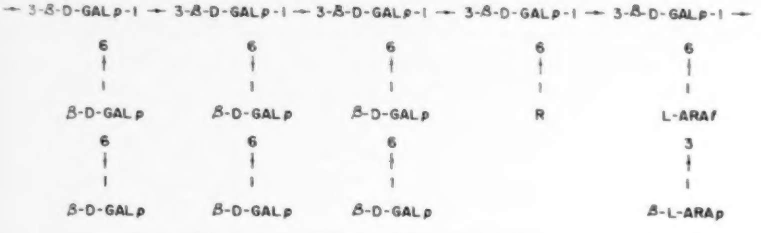
Glucomannan (fig. 6-5) consists of β-D-glucopyranose and β-D-mannopyranose residues linked together by (1- 4)-glycosidic bonds. In southern hardwoods the molar ratio of glucose to mannose is usually 1:2. It is not known whether these polysaccharides are branched or linear, or if they contain acetyl groups; their molecular properties are unknown (Timell 1965.)

→ 4-β-D-GLUp-1 → 4-β-D-MAN p-1 → 4-β-D-GLUp-1 → 4-β-D-MAN p-1 → 4-β-D-MAN p-1 →

Figure 6-5.—Repeating unit of glucomannan. Glu means glucose, and Man means mannose. (Drawing after Timell 1965.)

Pectin, which may comprise up to 17 percent of hardwood hemicelluloses, is water soluble mixed polysaccharide. The primary structure of pectin is obscure. It is a mixture of polygalacturonic acid with associated arabinan and galactan polymers that vary in proportion depending on the pectin source. The galacturonic acid residues are largely methyl esterified (Browning 1963; Timell 1965).

Arabinogalactans (fig. 6-6) of southern hardwoods have not been structurally characterized. Most knowledge of their structure is based on extensive work on larch (*Larix* spp.). Larch arabinogalactans are highly branched, water-soluble polysaccharides. Aqueous solutions have low viscosity. The polymer backbone is made up of (1- 3) linked-β-D-galactopyranose units, each of which has a side chain linked through the 6 position. The side chains are (1- 6) linked-β-D-galactopyranose residues for the most part, with some side chains of 3-o-β-C-arabinopyranosyl-L-arabinofuranose occurring. Lesser amounts of L-arabinofuranose and D-glucuronic acid are also present as terminal residues (Timell 1965; Browning 1963).


→ 3-β-D-GALp-1 → 3-β-D-GALp-1 → 3-β-D-GALp-1 → 3-β-D-GALp-1 → 3-β-D-GALp-1 →
6
1
β-D-GALp
β-D-GALp
β-D-GALp
R
L-ARAf
3
β-L-ARAp

R = β-D-GALACTOPYRANOSE OR, LESS FREQUENTLY, L-ARABINOFURANOSE OR D-GLUCOPYRANOSYLURONIC ACID

Figure 6-6.—Repeating unit of larch arabinogalactan. Gal means galactose; Ara means arabinose. (Drawing after Timell 1965.)

Uronic acid, acetyl, xylan, mannan, glucan, galactan, and **arabinan**—the constituent groups comprising hemicellulose and cellulose—are listed by quantity in tables 6-5 and 6-6. Their structures are shown in figure 6-7 in the form of their corresponding sugars and sugar acids. These sugars would be the end products isolated by hydrolysis of the polymers, e.g., xylan moiety-xylose. In the case of the acetyl functional group, acetic acid is the basic chemical unit released on hydrolysis.

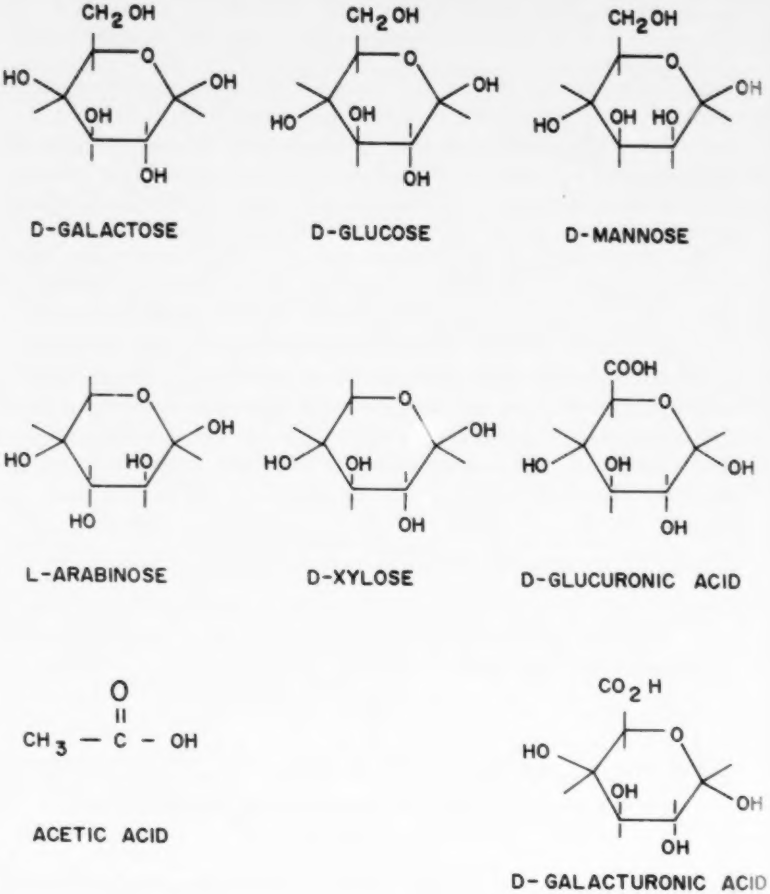

D-GALACTOSE
D-GLUCOSE
D-MANNOSE
L-ARABINOSE
D-XYLOSE
D-GLUCURONIC ACID
ACETIC ACID
D-GALACTURONIC ACID

Figure 6-7.—Structural formulae of eight hydrolysis products of hemicelluloses and cellulose. (Top) Three hexose sugars. (Middle) Two pentose sugars and D-glucuronic acid. (Bottom) Acetic acid and D-galacturonic acid. (Drawing after Herrick and Hergert 1977.)

6-5 LIGNIN[2]

Hardwood lignin is little utilized—except as fuel for pulp mills—although it is a plentiful and renewable raw material available throughout most of the world. In the future, however, lignin from both conifers and hardwoods may become an important feedstock for manufacture of certain chemicals traditionally derived from oil or natural gas.

In the South, pulp mills operate principally on southern pine wood; significant proportions of hardwood chips are also pulped, however, in mixture with pine chips. Because of different morphology, hardwoods behave differently from softwoods during pulping and afford a different type of fiber. More important, however, is the different structure of hardwood lignin which may upset pulping schedules if hardwoods constitute a significant fraction of the digester charge. Contamination of recovered softwood lignins by hardwood lignins could also affect schemes for lignin utilization. Knowledge of hardwood lignins may help to appraise the effects of including limited amounts of hardwoods in southern pine pulpwood.

For reasons both immediate and anticipated, therefore, the literature has been reviewed to provide an abstract of knowledge of lignin from southern hardwood species. Where data specific to the species that are the subject of this text are lacking, information on closely related species are included. Readers needing more information should study the more detailed data found in the references.

DEFINITION OF LIGNIN

The term lignin is often used loosely to refer to a class of phenolic plant polymers or various preparations derived in whole or in part from them (e.g., by pulping or other physical or chemical treatments of wood). Here the term lignin is used to mean the complex, naturally occurring phenolic phenylpropanoid polymer or "protolignin" characterized by the general empirical formula $C_9H_{8-X}0_2(H_2O)(_{<1.0}(OCH_3)_x)$ (Freudenberg and Neish 1968). More refined criteria for describing this type of lignin are developed in the following text. Other lignin preparations are referred to by names or abbreviations commonly used in the literature (Sarkanen and Ludwig 1971) such as Klason lignin, Bjorkman or milled wood lignin (MWL), Brauns native lignin (BNL), and dioxane lignin (DL). MWL is widely considered to be the most representative isolated lignin preparation. BNL is lower in molecular weight, more highly oxidized, and does not reflect the true syringyl to guaiacyl ratio of hardwood sources. DL contains Hibbert Ketone structures (phenylpropanoids with ketonic groups in the side chain formed by hydrolysis of ether bonds) and a high proportion of condensed structures due to acid-catalyzed carbon-carbon cross-linking.

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[2] The text under this heading is taken virtually verbatim from Bleam and Harkin (1975) by permission of the authors and the Forest Products Research Society.

LIGNIN CONTENT IN HARDWOODS

Hardwood lignin determination by the Klason method (digestion of wood meal with 72 percent H_2SO_4, dilution, and gravimetric assay of the insoluble residue) gives low values because lignin fragments remain soluble in the dilute acid (Sarkanen and Ludwig 1971). However, its convenience makes it the assay method most commonly used. Table 6-9 shows Klason lignin contents and some methoxyl (MeO) data for some southern hardwoods. In general, hardwoods yield 19 to 25 percent.

Lignin contents (tables 6-1 and 6-2) reported by Hergert et al.[1] include the fraction insoluble in 72-percent sulfuric acid (**Klason lignin**) and the fraction solubilized during the isolation procedure, i.e., the acid-soluble lignin. Since the latter amounts of 2.5 to 6.0 percent of wood (Musha and Goring 1974), and has rarely been reported in earlier studies of the summative analyses of wood, values of Hergert et al.[1] are generally higher than those from older literature summarized in table 6-9 or in the review of Fengel and Grosser (1975). Also included in the lignin fraction indicated in tables 6-1 and 6-2 are those phenolic lignin-like polymers deposited upon the death of the parenchyma cells (Hergert 1977).

The ratio of acid soluble lignin to insoluble lignin is a rough indicator of the proportion of syringyl to guaiacyl groups in lignin; the higher this number, the higher the syringyl content (table 6-10). Since **syringyl lignins** are generally easier to remove from wood than **guaiacyl lignins** during chemical pulping, those samples with a high ratio of soluble to insoluble lignin ought to be more readily pulped than other hardwoods. From table 6-10, sweetgum, loblolly-bay, and water oak appear to be readily pulpable (Hergert et al.[1]).

TABLE 6-9.—*Klason lignin and its methoxyl content in hardwoods growing on southern pine sites* (Bleam and Harkin 1975)

Species	Klason Lignin[1]	Methoxyl content	Source of data[2]
	Percent of dry wood	*Percent of Klason lignin*	
Ash, green	25.8	—	a
Ash, white	18.5 - 26.4	—	a, d
Elm, American	20.5 - 29.0	20.0 - 25.0	a, b, d
Hackberry	20.7	—	a
Hickory, mockernut	18.9 - 22.8	—	a
Hickory, pignut	21.9 - 22.5	—	a, b
Hickory, sand[3]	22.7	—	a
Hickory, shagbark	21.4 - 23.4	—	a
Maple, red	20.6 - 24.0	25.3	a, b, d
Magnolia[4]	27.5	20.7	a
Oak, black	24.0	—	a
Oak, blackjack	26.3	—	a
Oak, northern red	23.9 - 25.2	—	a
Oak, post	24.0	—	a
Oak, scarlet	21.7	—	a

TABLE 6-9.—*Klason lignin and its methoxyl content in hardwoods growing on southern pine sites* (Bleam and Harkin 1975)—Continued

Species	Klason Lignin[1]	Methoxyl content	Source of data[2]
	Percent of dry wood	*Percent of Klason lignin*	
Oak, southern red	23.9 - 25.0	—	a
Oak, white	25.8 - 32.0	18.5 - 25.4	a, b, c
Sweetgum	20.3 - 23.7	—	a
Tupelo, black	24.6 - 28.6	19.8 - 22.9	a, b, c
Yellow-poplar	20.0 - 23.9	24.9 - 25.9	a, b, d, e

[1] Unextracted basis.

[2] (a) Unpublished data from U.S. Forest Products Laboratory, Service, courtesy of Marilyn J. Effland; (b) Wise and Jahn 1952; (c) Brauns and Brauns 1960; (d) Chang and Sarkanen 1973; (e) Klauditz 1958.

[3] *Carya pallida* (Ashe) Engl. & Graebn.

[4] *Magnolia obovata.*

TABLE 6-10.—*Ratio of soluble to insoluble lignin in 72-percent sulfuric acid, for 19 southern hardwood species* (Hergert et al., see text footnote[1])

Species	Site[1]	Ratio
PRINCIPAL PINE-SITE HARDWOODS		
Ash, white	G	0.074
Elm, American[2]	G	.060
Elm, American[3]	T	.107
Hickory sp.	G	.079
Maple, red	G	.120
Oak, post	G	.145
Oak, southern red	G	.170
Oak, water	G	.206
Oak, white	G	.168
Sweetbay	G	.121
Sweetgum[2]	G	.140
Sweetgum[4]	G	.147
Tupelo, black	G	.100
MINOR PINE-SITE HARDWOODS		
Cottonwood[5]	G	0.123
Cottonwood[6]	G	.124
Loblolly-bay	G	.220
Oak, bear	G	.087
Oak, live	G	.111
Pecan	G	.105
Red bay	G	.102
Sycamore	G	.124
Tupelo, water	G	.124

[1] G means southeastern Georgia; T means eastern Tennessee. Except for species with footnotes 3, 4, 5, and 6, number of trees in sample unknown.

[2] Twenty trees.

[3] Single tree, dimensions not recorded.

[4] Single tree, 7.1-in. diameter, 39 years old.

[5] Two trees, 32 years old.

[6] Two trees, 46 years old.

FORMATION OF LIGNIN

The complexity of lignin derives from the variation in structure of its three main immediate precursors or **lignols** (the p-hydroxycinnamyl alcohols shown in fig. 6-8) and from the mechanism of polymerization (Harkin 1967, 1973; Sarkanen and Ludwig 1971). In beech (*Fagus* spp.), a typical hardwood, about 56 percent of the phenylpropanoid monomeric units of the lignin are of the **syringyl**[3] (4-hydroxy-3,5-dimethoxyphenyl) type derived from sinapyl alcohol; 40 percent are of the **guaiacyl** (4-hydroxy-3-methoxyphenyl) type derived from coniferyl alcohol; and 4 percent are of the 4-hydroxyphenyl type derived from p-coumaryl alcohol (Nimz 1974). The relative proportions of precursor molecules (lignol) residues in plant lignins vary considerably from species to species, as discussed later.

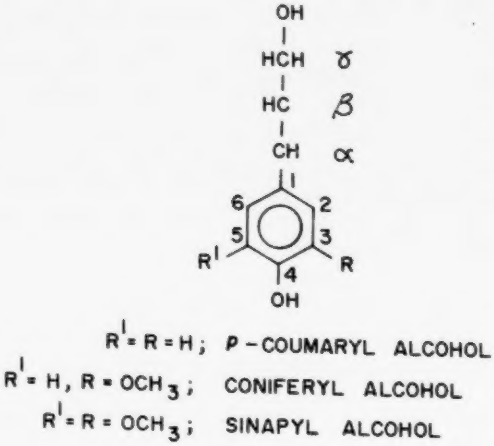
OH
HCH
γ
HC
β
CH
α
1
2
3
4
5
6
R
R'
OH
R' = R = H ; P – COUMARYL ALCOHOL
R' = H, R = OCH3 ; CONIFERYL ALCOHOL
R' = R = OCH3 ; SINAPYL ALCOHOL

Figure 6-8.—Structures of the three main phenylpropanoid precursors of lignin (monolignols). (Drawing after Bleam and Harkin 1975.)

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[3] Lignin chemists conventionally use the term "syringyl" erroneously to describe the 3,5-dimethoxy-4-hydroxyphenyl grouping, whereas it correctly refers to the 3,5-dimethoxy-4-hydroxybenzyl grouping, as in syringyl alcohol.

Each lignol is oxidized in the cambial zone of the maturing plant to a phenoxyl radical by a peroxidase (Harkin and Obst 1973). The radical is stabilized by mesomerism and reacts through limiting structures depicted in fig. 6-9. Polymerization is effected through interlignol bonds formed by a multiplicity of mechanisms, including radical pairing, radical transfer with subsequent pairing, and additions to unstable quinone methides formed by radical pairing. Initial coupling is followed by various types of stabilization reactions that form additional interlignol bonds. For discussions of these complicated coupling and stabilization reactions see Harkin (1967, 1973), and Sarkanen and Ludwig (1971). The various carbon-carbon and ether bonds formed are commonly referred to by the number and letter locants (as in fig. 6-8) of the atoms joined, e.g., a 5-5 bond joins the carbons at position 5 in each of two adjacent rings, and a β-0-4 linkage is an ether bond between a β-carbon of a side chain and the carbon at position 4 of a neighboring ring. Multiple linkages are referred to by trivial names of compounds containing them, e.g., pinoresinol-type linkages and phenylcoumarans (see units 21/22 and 24/25 in fig. 6-10).

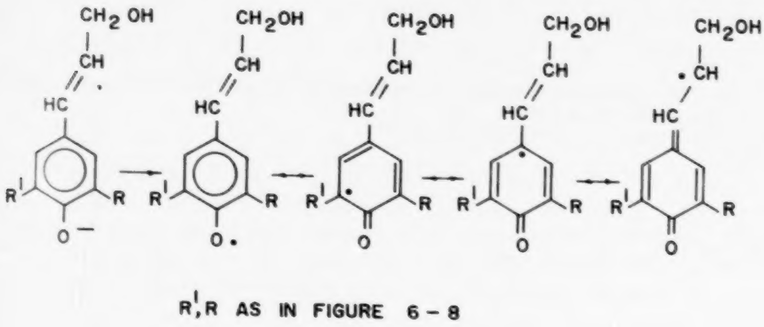

Figure 6-9.—Four main mesomeric forms of the free radical produced by phenol oxidation of a monolignol phenoxide ion. (Drawing after Bleam and Harkin 1975.)

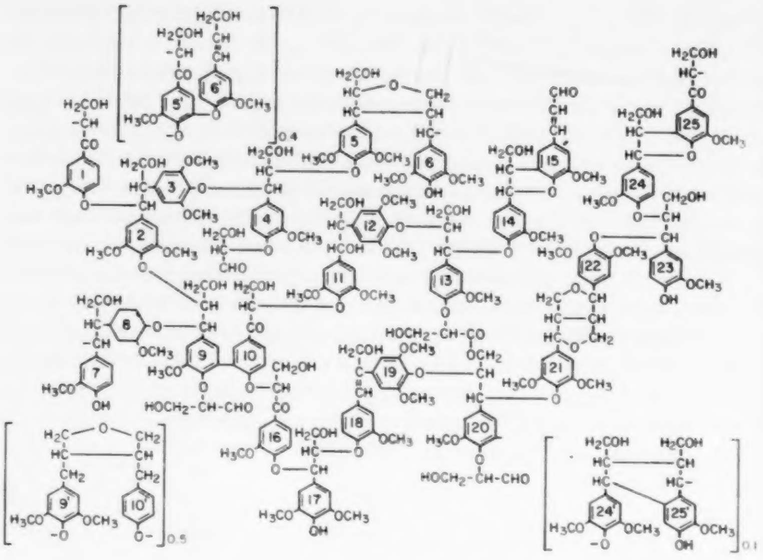

Figure 6-10.—Schematic formula of a representative portion of a hardwood lignin. (Drawing after Nimz 1974.)

Two factors influencing the structure of lignin are the proportions of p-coumaryl, coniferyl, and sinapyl alcohols incorporated and the reaction conditions. The methoxylation pattern of the aromatic ring in each lignol influences the relative reactivity of the radical sites due to electronic and steric effects. Reaction conditions during polymerization, particularly the relative concentrations of lignol radicals and reactive sites in preformed lignin aggregates (oligolignols), determine whether the lignin contains more **bulk polymer** or **endwise polymer** character. Bulk polymers are formed when radicals couple more frequently with other monolignol radicals than with radical sites in the growing polymer and contain larger proportions of pinoresinol-type structures, 5,5-biphenyls, and 4-0-5 ether linkages (Sarkanen and Ludwig 1971).

INDICATORS FOR MAKEUP OF HARDWOOD LIGNINS

The methoxyl content of a lignin gives a rough primary indication of the amounts and types of lignols from which it has been formed. The methoxyl content per lignol (MeO/C_9) can be calculated from analytical data (Fergus and Goring 1970ab). By disregarding the normally low content of 4-hydroxyphenyl units in hardwood lignins, the percentage of syringyl units can be estimated directly from this value. Analytical data from some pertinent hardwood lignin preparations are given in table 6-11. Most hardwoods contain 1.20 to 1.60 MeO/C_9 and thus approximately 20 to 60 percent syringyl units.

Syringyl contents can be estimated from the extinction coefficients at 280 nm of $NaBH_4$-reduced MWL and by calculation of relative absorbance $A_0/A_{1500}cm^{-1}$ for various bands in the IR spectrum (Sarkanen and Ludwig 1971). In lignins of some hardwoods (e.g., *Populus deltoides*) p-hydroxybenzoate esters interfere with this method.

Variation in the proportions of syringylpropane and guaiacylpropane units in hardwood lignins is often measured by an S/V ratio obtained by alkaline nitrobenzene oxidation of wood or lignin to yield the aromatic aldehydes, syringaldehyde (S) and vanillin (V), which are separated and determined quantitatively (e.g., by gas chromatography). Results of this determination are presented in table 6-12. The S/V ratio is roughly three times the ratio of syringyl to guaiacyl nuclei in the lignin (Sarkanen and Ludwig 1971).

TABLE 6-11.—*Carbon, hdyrogen, and methoxyl content of representative hardwood lignins and their methoxyl content per lignol* (Bleam and Harkin 1975)

Species	Lignin type	C	H	MeO	MEO/C_9[1]	Source of data[2]
		-----*Percent*-----				
Liquidambar styraciflua	MWL	59.6	6.0	21.4	1.45	a
Quercus spp.	MWL	58.6	6.4	19.5	1.20	b
	BNL	58.6	5.3	14.8	0.98	b
Q. rubra[3]	thioglycolic acid	62.7	5.7	22.1	1.42	c
Acer spp.	periodate	58.4	5.4	20.4	1.40	c
	BNL	61.0	5.6	17.4	1.12	d
	solvolysis (liq. NH_3	58.2	6.4	21.6	1.52	e
A. macrophyllum	MWL	60.4	5.7	20.0	1.32	c
A. platanoides[3]	thioglycolic acid	64.5	6.3	23.0	1.44	c
Fraxinus spp.	BNL	61.0	5.6	17.4	1.12	d
F. excelsior[3]	thioglycolic acid	63.8	6.0	23.8	1.48	c
Ulmus montana[3]	thioglycolic acid	63.2	5.8	19.8	1.24	c
Magnolia soulangeana[3]	thioglycolic acid	63.9	5.9	22.4	1.41	c
Hardwood average	dioxane	59.0	5.5	21.5	1.49	f

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[1] Calculated by method of Freudenberg and Neish (1968); expressed as the number of groups per lignol.

[2] (a) Kirk and Lundquist (1970); (b) Coscia et al. (1961); (c) Sarkanen and Ludwig (1971, ch. 3, p. 64); (d) DeStevens and Nord (1954); (e) Pepper (1958); (f) Arseneau and Pepper (1965).

[3] Recalculated on a thioacetate-free basis by the method of Freudenberg and Neish (1968).

TABLE 6-12.—*Alkaline nitrobenzene oxidation products of five southern hardwoods* (After Chang and Sarkanen 1973)

Species	Total aldehydes (percent of lignin)	S/V[1] (molar ratio)
Ash, white	48.6	2.8
Elm, American	40.9	2.6
Maple, red	46.0	2.8
Oak, northern red	47.2	2.8
Yellow-poplar	49.2	2.7

[1] S means syringaldehyde; V means vanillin.

Variations in S/V ratios within a species correlate roughly with lignin content, being higher in trees growing in temperate climates than those growing in tropical climates (Kawamura and Bland 1967). This suggests that some data for the species being emphasized here might not be transferable if values were obtained from specimens not grown on southern pine sites.

The S/V ratio increases with age for *Populus nigra* and other hardwoods (Venverloo 1971). Primary xylem contains no syringyl units detectable by spectroscopic or chemical methods. Mature xylem also was shown to be richer in p-hydroxybenzoate groups. Foliage is lower in the yield of total aldehydes and S/V ratio as well as lignin content compared to the wood of *Magnolia obovata* (Sarkanen and Ludwig 1971).

Lignin in hardwoods may not be of homogeneous composition throughout the wood cell walls and tissues; some layers may have lignin with higher proportions of syringyl units than others. So-called "syringyl" and "guaiacyl" lignins—i.e., lignins derived mainly from sinapyl and coniferyl alcohol—are segregated within the birch *Betula papyrifera* (Fergus and Goring 1970a,b). The UV absorption maxima (λ_{max}) of various cell wall types and divisions suggest that fiber and ray parenchyma secondary cell walls contain syringyl lignin (λ_{max} = 270 nm). Vessel secondary cell walls and certain lamella regions contain guaiacyl lignin (λ_{max} = 280 nm). Fiber cell corners of middle lamellae contain a mixed guiaicyl-syringyl lignin (λ_{max} = 275 nm). This compartmentalization could be important for structural considerations because endwise polymerization appears to increase with the syringyl content of **synthetic lignins (dehydrogenation polymers)** prepared from coniferyl alcohol-sinapyl alcohol mixtures (Pearl 1974). A DHP recently made from a sinapyl alcohol alone yielded typical lignin degradation products (Yamasaki et al. 1973). Thus, lignin derived exclusively from sinapyl alcohol may occur in parts of hardwood cells.

STRUCTURES IN HARDWOOD LIGNINS

Methods developed to study conifer lignins have recently been applied to hardwood lignins and have shown that similar structures occur in both types. However, if hardwoods contain compartmentalized lignins with varying syringyl content (Fergus and Goring 1970a,b), results for the total lignin may reflect averages from lignins of differing types. Part of hardwood lignin may be very similar to conifer lignin; part may be predominantly syringyl, having much greater endwise polymer character; and part may be a mixed polymer with intermediate properties. Some of the structures and bond types known to occur in the total lignin and the approximate amounts of each are now discussed.

α- and β-ethers.—The most common intermonomer linkages in any lignin are α-0-4 and β-0-4 ethers; excluding phenylcoumaran linkages (cyclic α-0-4 ethers, see below), these constitute 53 percent of the linkages in spruce (Sarkanen and Ludwig 1971) and 65 percent in beech (Nimz 1974). These are the main bonds cleaved by chemical pulping. β-0-4 ethers have been qualitatively determined by alcoholysis, acidolysis, mild solvolysis, and hydrogenolysis.

Hibbert ketones, which arise exclusively from β-0-4 linked units on acid hydrdolysis, are commonly obtained from hardwoods (Sarkanen and Ludwig 1971). The ratio of syringyl to guaiacyl ketones is approximately the same as the S/V ratio. Dimers, trimers, and a tetramer containing the β-0-4 linkage have been isolated from beech (*Fagus sylvatica*) and spruce (*Picea excelsa*) after treatment with boiling water (Nimz 1974). A dimer and a trimer containing this linkage was found after treatment of ash (*Fraxinus mandshurica*) with dioxane-water at 180°C (Omori and Sakakibara 1972, 1974). Dimers containing β-0-4 linkages were obtained by neutral hydrogenolysis of *Acer saccharum* (Bhaskaran and Schuerch 1969).

Quantitation is usually indirect. Ethanolysis or acidolysis generates approximately one γ-methyl group per β-ether cleaved. Determinations of γ-methyl groups indicate the β-ether content of spruce MWL is about 25 to 33 percent (Sarkanen and Ludwig 1971). No values have been determined in this way for hardwood lignins but quantitative cleavage of α- and β-ethers in beech lignin with thioacetic acid/boron triflouride (TA/BF_3) indicates a combined content of 65 percent (Nimz 1974). Relative numbers of bonds cleaved were calculated from the amounts of monomers, dimers, trimers, etc. produced. He estimated 28 percent α-0-4 ether linkages for beech lignin. Although α-ethers are known to exist in lignin from its reactions, fragments containing these ethers are not easy to isolate because they hydrolyze so readily. From the increase in phenolic hydroxyl after cold methanolysis Sarkanen and Ludwig (1971) computed the α-0-4 ether content of spruce MWL is about 8 to 10 percent. The yield of soluble products of beech, from boiling water hydrolysis which cleaves α-0-4 linkages, was twice the yield from spruce. In fig. 6-10, α-0-4 ether bonds occur at units 2/1, 4/3, 9/8, 13/14, 17/16, 20/21, and 23/22; β-0-4 ethers occur at 2/3, 4/5, 7/8, 10/11, 13/12, 16/10, 17/18, 20/19, and 23/24.

β-1 linkages.—The β-1 linkage in spruce and beech lignin has been demonstrated by isolation of dimers, trimers, and a tetramer following mild hydrolysis in boiling water or TA/BF_3 treatment (Nimz 1974). A dimer with a β-1 linkage was also isolated from maple and ash (Bhaskaran and Schuerch 1969; Miller and Schuerch 1968; Sarkanen and Ludwig 1971; Sudo and Sakakibara 1973). The content of nonconjugated carbonyls in MWL may be correlated to β-1 linkage structures assuming that β-ketones arise from side chain displacement. Only 0.05 nonconjugated carbonyl was found per C_9 unit in mixed birch (*Betula verrucosa* and *B. pubescens*) MWL (Klemola 1958). Some 15 percent of the units in beech lignin appear to be linked by β-1 bonds on the basis of relative yields of dimers containing this bond after TA/BF_3 treatment (Nimz 1974). Units 2/3, 7/8, 11/12, and 18/19 in fig. 6-10 are linked by β-1 bonds.

β-5 (Phenylcoumaran) structures.—Dehydrodiconiferyl alcohol and other phenylcoumarans were isolated after acidolysis of spruce (Sarkanen and Ludwig 1971). Alkaline hydrogenolysis of maple (Miller and Schuerch 1968) yielded a diarylethane, thought to arise by reduction of a stilbene formed by alkaline hydrolysis of a phenylcoumaran. Similar structures have been isolated by TA/BF_3 treatment of beech (Nimz 1974). Permanganate oxidation of hardwoods yields 5-carboxyvanillic acid, derived in part from phenylcoumarans; yields are generally 1 to 2 percent of the lignin oxidized (Erickson et al. 1973). Spectrometric assays of stilbenes and phenylcoumarans found during acidolysis gave estimates of 8 to 11 percent for spruce lignin (Sarkanen and Ludwig 1971). Nonetherified phenylcoumarans and stilbenes in birch DL are placed at less than 2 percent (Klemola 1958), indicating less than 6.5 percent phenylcoumarans in the original lignin based on a hydroxyl content of 38 percent and a conversion of 80 percent. A figure of 6 percent for beech based on TA/BF treatment (Nimz 1974) agrees with spectrometric estimates of 6.5 to 7 percent (Suty and Golis 1972). Phenylcoumaran structures occur at units 14/15 and 24/25 in figure 6-10.

Pinoresinol-type linkages.—Pinoresinol-type compounds have been isolated from birch (Klemola 1958), ash (Omori and Sakakibara 1971, 1972, 1974), and beech (Nimz 1974) following mild solvolysis, and from ash (Sudo and Sakakibara 1973) after hydrogenolysis. Indirect evidence for this structure was obtained by isolation of a dilactone released from lignin with HNO_3 (Sarkanen and Ludwig 1971). About 5 percent of the linkages of beech lignin (see units 21/22 in fig. 6-10) are of this type (Nimz 1974).

5-5 (Biphenyl) linkages.—Pew (Sarkanen and Ludwig 1971) first proposed the biphenyl linkage on the basis of nitrobenzene oxidation of spruce. Biphenyl linkages have since been demonstrated by solvolysis of birch (Klemola 1958) and hydrogenolysis of maple (Bhaskaran and Schuerch 1969; Miller and Schuerch 1968; Sarkanen and Ludwig 1971) and ash (Sudo and Sakakibara 1973). Dehydrodiveratric acid is commonly obtained from permanganate oxidation of kraft lignins in yields of approximately 1 percent. The biphenyl content of beech was placed at 2.3 percent on the basis of biphenyl yields on TA/BF_3 degradation (Nimz 1974). An estimate of 20 percent for beech based on spectrometric data (Suty and Golis 1972) is unreliable due to uncertainties associated with the method. Units 9 and 10 in fig. 6-10 are connected by a 5,5-biphenyl bond.

Other β-β linkages.—Evidence for β-β linkages other than pinoresinol-type linkages has been obtained. 1- Syringyl-2-hydroxymethyl-3-syringoyltetrahydrofuran was isolated from a hydrolysate of ash (Omori and Sakakibara 1974) and 2.0 percent 2,3 disyringyltetrahydrofuran-type linkages and 0.5 percent tetralin (β-β/α-6) linkages (see units 9'/10' and 24'/25' in fig. 6-10) were estimated for beech lignin based on yields of dimers from TA/BF_3 treatment (Nimz 1974).

Nimz (1974) also isolated dimers containing α-β linkages from beech and estimated their frequency at 2.5 percent (see units 5/6 in fig. 6-10).

Other minor interunitary linkages which may occur in lignin are discussed by Sarkanen and Ludwig (1971).

Functional groups in hardwood lignins.—Various functional groups can be determined in lignin preparations by chemical, spectrometric, or combined methods. A detailed discussion of methodology is given by Sarkanen and Ludwig (1971). Some analytical results are summarized in table 6-13.

Structural formula for hardwood lignin.—The structure of softwood lignin was derived mainly by identification of intermediates of biosynthesis of lignin and collating their structures with chemical analytical data (Freudenberg and Neish 1968; Sarkanen and Ludwig 1971). The structure of hardwood lignins has been derived mainly by identification of the structures of degradation products and confirmed by nuclear magnetic resonance spectroscopy (Nimz 1974).

TABLE 6-13.—*Number of functional groups per lignol in lignins (i.e., functional group /C_9) from representative hardwood species (Bleam and Harkin 1975)*

Hardwood lignin	Total carbonyl[1]	α-Carbonyl[2]	Conjugated aldehydes[3]	Total hydroxyl	Phenolic hydroxyl	4-hydroxybenyl alcohol[3]	Total α-hydroxyl	Unsaturated side chains[2]	Source of data[9]
Birch[4]	0.12	0.05	0.02	1.29[5]	0.26[2,5]	0.04	0.45[7]	0.02	a, b
Birch[6]	.13	.05	.02	1.30[5]	.38[2,5]	.04	.45[7], .47[5]	.02	a, b
Beech[4]	—	.04	.02	1.53[5]	.30[2], .37[5]	.04	—	.06	a, c, d
Eucalyptus[4]	.15	—	—	—	—	.05	—	—	a
Aspen	—	—	—	1.04[5,6]	.28[5,6]	.06[4]	.40[6,7], .50[5,6]	—	a
Tupelo, black[6]	—	—	—	1.12[8]	.37[5]	—	—	—	e

[1] Hydroxylamine hydrochloride method.
[2] Spectrophotometric $\Delta\varepsilon$ method.
[3] Quinone monochloroimine method.
[4] Data for MWL.
[5] Obtained by ^{1}H-NMR spectroscopy.
[6] Data for dioxane lignin.
[7] Methanol/HC1 method.
[8] Acetylation method.
[9] (a) Sarkanen and Ludwig (1971); (b) Klemola (1958); (c) Nimz (1974); (d) Suty and Golis (1972); (e) Lenz (1968)

Primarily on the basis of yields and structures of fragments obtained by TA/ BF_3 degradation of beechwood, Nimz (1974) proposed a structural scheme for hardwood lignin (fig. 6-10). It is quantitatively consistent with published data for the C_9 formula of beech MWL, degradation data, content of phenylcoumaran structures, unsaturated side chains, and the relative number of aryl and α-vinylic protons found in the MWL by 1H-NMR spectroscopy. It is qualitatively consistent with all of the data reviewed here and the ^{13}C-NMR spectrum of MWL. The structure represented in figure 6-10 differs in relative numbers of aliphatic hydroxyls, phenolic hydroxyls, conjugated carbonyls, and biphenyl linkages from those reported for MWL of beech (Nimz 1974; Suty and Golis 1972). However, values for the hydroxyl contents of MWL are not absolute; MWL is only one-third of the total lignin; and the remainder is probably more highly condensed. Some hydroxyls are probably introduced into MWL during milling, and carbohydrate impurities in MWL inflate its hydroxyl content. The content of conjugated carbonyls is about four times greater and biphenyl content is an order of magnitude lower than values reported by Suty and Golis (1972). Although the spectrophotometric method they used is imprecise, the magnitude of these differences indicates a need for clarification by independent methods. The total carbonyl content of the structural formula is also higher than the total carbonyl content of other hardwood lignins (table 6-13).

LIGNIN-CARBOHYDRATE BONDING

Most evidence in the literature on lignin-carbohydrate bonding (Grushnikov and Shorygina 1970; Sarkanen and Ludwig 1971) strongly supports the existence of chemical bonds between lignin and carbohydrates in wood. Many investigators who have isolated lignin-carbohydrate complexes (LCC) have failed to separate the components by paper and column chromatography, electrophoresis, solvent fractionation, and partition. Acid or base hydrolysis usually releases some but not always all the carbohydrate from such complexes.

The bonds could be ether, ester, or glycoside bonds, or various C-C and C-O bonds formed by radical transfer during lignin formation. In model experiments, sucrose was grafted during polymerization into a DHP by nucleophilic addition to a quinone methide or by a radical transfer mechanism (Grushnikov and Shorygina 1970; Harkin 1967; Sarkanen and Ludwig 1971). Methanolysis and NaOH hydrolysis support the presence of uronic esters in LCC from maple and eucalyptus (Grushnikov and Shorygina 1970; Stewart 1973). The stability of part of the uronic acid-lignin complex suggests that stable ether bonds are involved (Stewart 1973). Some glycosidic linkages in LCCs have been proposed on the basis of enzymatic cleavage, acid hydrolysis kinetics, and the isolation of tri-O-methylxylose from a methylated, then acid-hydrolyzed beech LCC (Grushnikov and Shorygina 1970).

PHYSICAL AND CHEMICAL PROPERTIES OF HARDWOOD LIGNIN

Lignin *in situ* is considered to be an infinitely large polymer (due to its three-dimensional structure and cross-linking with carbohydrates) which occurs between wood cells and penetrates the cell wall polysaccharides. It is, therefore, necessary to break it down to smaller pieces and introduce polar groups to make it soluble (Bolker 1970). Most soluble lignin preparations are polydisperse. Lignosulfonates, for example, have been fractionated and shown to contain units from more than 10^6 daltons to fewer than 3,700 (Sarkanen and Ludwig 1971). Various pulping processes and enzymatic degradation show increasing molecular weight of the fractions solubilized as a function of time (Sarkanen and Ludwig 1971; Yean and Goring 1970).

Solubilized lignin particles behave as nonswelled spheres as shown by the intrinsic viscosity (Sarkanen and Ludwig 1971). During degradation by α-ether cleavage, lignin behaves as a cross-linked network of performed chains of average $DP \approx 19$ (Bolker 1970).

IMPLICATIONS

Lignin must be altered in, or removed from, wood to permit utilization of wood polysaccharides (Harkin 1973). The ether linkages in lignin are the bonds most susceptible to cleavage, allowing extensive fragmentation and increasing polarity, enhancing lignin removal from wood. The relative proportion of ether linkages increases with the endwise polymer character of lignin (Sarkanen and Ludwig 1971), which is thought to increase with syringyl content (Pearl 1974; Sarkanen and Ludwig 1971), and is thus more predominant in hardwood lignins. This relationship is supported by the rate constants for kraft delignification of woods with varying syringylpropane content (Chang and Sarkanen 1973). If generally true, these relationships may be especially useful in the rapid characterization of lignin for hardwood utilization purposes.

The formulation of a structural scheme for a typical hardwood based on extensive degradation data provides a foundation upon which future wood and lignin utilization schemes can be built.

Readers wishing to study lignin utilization will find the following publications useful:

Reference	Title
Falkhag (1975)	Lignin in materials
Goldstein (1975)	Perspectives on production of phenols and phenolic acids from lignin and bark
Lindberg et al. (1975)	Lignin as a raw material for synthetic polymers
Vorher and Schweers (1975)	Utilization of phenol lignin
Enkvist (1975)	Phenolics and other organic chemicals from kraft black liquors by disproportionation and cracking reactions
Hsu and Glasser (1975)	Polyurethane foams from carboxylated lignins

6-6 EXTRACTIVES[4]

Wood and bark extractives from hardwoods of the eastern United States are little used commercially. Extractives are nevertheless important in the utilization of these hardwoods because of their contribution to wood properties. The extractives can protect wood from decay, add color and odor to wood, accent grain pattern, and enhance strength properties. In contrast, they can contribute to corrosion of metals in contact with wood; inhibit setting of concrete, glues, and finishes; cause various problems during papermaking; present health hazards (e.g., dermatitis, asthma, and cancer); and affect the color stability of wood to light. Seldom can all color be removed from wood or bark by extraction because of polymerization of the extractives into insoluble deposits.

The chemistry of extractives from the wood and bark of pine-site hardwoods is complex. In this section, extractives are defined, percentages in stemwood and branchwood are tabulated, and sources and classes of extractives are discussed. Following this introduction available information on chemical constituents of extractives of pine-site hardwood species are presented in alphabetical order of species common names. Quantitative data on extractives content of the major pine-site species are presented in tables 6-7, 6-14, and in chapters 13 and 14.

DEFINITION AND DISTRIBUTION

Extractives are natural products extraneous to a lignocellulose cell wall; they can be removed with inert solvents such as ether, benzene-alcohol (2:1 vol/vol), acetone, and cold water. Although cold water is considered inert, hot water will cause a slight, slow degradation of the lignocellulosic cell wall. Extractives may be within a cell wall, but are not chemically attached to it. In addition to extractives, cells may contain such insoluble extraneous constituents as crystalline inclusions of calcium oxalate and silica, starch granules, and certain polymeric materials.

Inner bark and sapwood generally are rich in simple monomers and nutrients such as fats, starch, sucrose, simple sugars, inositols, simple glycosides, free and esterified sterols, and phenylpropanoids and other simple phenolics. Heartwood and outer bark, by contrast tend to be deficient in nutrients, glycosides and metabolic intermediates, but are rich in compounds such as hydrolyzable and condensed tannins and many other phenolics, alkaloids, resins, essential oils, and specialized compounds of a wide variety of types. Heartwood and outer bark may also contain the various gums, kinos, and balsams that have evolved as part of the wound response mechanisms, as well as the compounds capable of protecting these metabolically inactive tissues against biological attack.

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[4] The text under this heading is taken, by permission of the authors, from passages in Rowe and Conner (1979) pertinent to the major hardwood species (Section 2-5) that grow on southern pine sites; readers needing fuller information on all eastern hardwood species should consult their more comprehensive review. Tabular data on percentages of extractives in wood are from Hergert et al.[1] and from unpublished data in Final Report FS-SO-3201-1.41, dated March 19, 1981, U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Pineville, La.

QUANTITIES IN WOOD AND BARK

Hergert et al.[1] found that total extractives in various-diameter stemwood of Georgia and Tennessee hardwoods ranged from about one percent to over 13 percent (tables 6-7 and 6-8), and that upland hardwoods from eastern Tennessee had average stemwood extractives content of 4.5 percent of unextracted dry weight. Of the total extractives content in eastern hardwoods, less than one-third is soluble in petroleum ether (**resin**)[5], generally more than one-third is soluble in ether but insoluble in petroleum ether or soluble in acetone and insoluble in ether (**phenolics**), and usually about one-third is soluble in water and insoluble in acetone (**carbohydrates**). (See tables 6-7 and 6-8.)

Stemwood samples of 6-inch pine-site hardwoods collected Southwide (see table 3-1) varied from a low of 2.34 percent in sweetgum to 6.87 percent in blackjack oak; stemwood of all 22 species had average extractives content of 4.90 percent of unextracted dry weight. Branchwood averaged higher in extractives content (5.66 percent) than stemwood (table 6-14).

Stembark of these 6-inch pine-site hardwoods varied from a low of 7.97 percent in hackberry to 18.45 percent in yellow-poplar; stembark of the 22 species had average extractives content of 14.41 percent. Branchbark averaged higher in extractives content (16.65 percent) than stembark. Both green and white ash had branchbark extractives content greater than 20 percent (table 6-14).

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[5] The term **resin** to denote petroleum ether extractives is usual in discussing southern pine extractives. It is used here for convenience; these extractives from hardwoods are almost entirely fats—soft semi-solids or oils.

TABLE 6-14.—*Extractives content in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] *(Data from Manwiller*[3]*)*

Species	Stemwood[4]	Stembark[4]	Branchwood[5]	Branchbark[5]
	---------Percentage of unextracted ovendry weight---------			
Ash, green	6.23	17.57	7.46	21.80
	(.78)	(2.01)	(1.26)	(3.99)
Ash, white	6.09	17.02	7.51	20.88
	(.79)	(2.59)	(1.13)	(3.00)
Elm, American	4.20	12.40	5.07	15.78
	(.88)	(3.19)	(.69)	(2.63)
Elm, Winged	4.04	14.18	5.57	14.87
	(.71)	(1.78)	(.76)	(1.83)
Hackberry[6]	5.53	7.97	6.66	10.61
	(.91)	(1.06)	(.67)	(1.72)
Hickory, sp.	5.35	18.01	6.31	18.89
	(.71)	(2.52)	(.73)	(3.23)
Maple, red	3.84	16.36	4.12	18.66
	(.65)	(1.23)	(.57)	(3.44)
Oak, black	5.82	17.48	6.14	18.53
	(.91)	(2.78)	(.54)	(2.26)

TABLE 6-14.—*Extractives content in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] *(Data from Manwiller*[3]*)—Continued*

Species	Stemwood[4]	Stembark[4]	Branchwood[5]	Branchbark[5]
	--------Percentage of unextracted ovendry weight--------			
Oak, blackjack	6.87	16.00	7.86	19.20
	(1.11)	(1.92)	(1.74)	(2.69)
Oak, cherrybark	4.95	12.84	5.31	14.63
	(1.07)	(2.61)	(.83)	(2.08)
Oak, laurel	5.09	12.93	6.08	13.72
	(.69)	(3.16)	(.72)	(2.58)
Oak, northern red	6.04	13.39	5.88	14.55
	(1.01)	(2.57)	(.92)	(3.16)
Oak, post	6.12	13.05	6.87	16.50
	(.80)	(1.52)	(.51)	(2.10)
Oak, scarlet	6.07	15.08	6.14	16.14
	(.73)	(.94)	(.80)	(1.58)
Oak, Shumard	5.77	13.91	6.24	15.75
	(1.00)	(2.61)	(1.04)	(3.00)
Oak, southern red	4.96	14.72	6.15	15.74
	(.56)	(1.38)	(.76)	(1.93)
Oak, water	4.67	11.28	5.60	14.50
	(.75)	(1.16)	(.97)	(2.08)
Oak, white	4.99	12.92	5.87	16.34
	(1.05)	(2.54)	(.99)	(2.38)
Sweetbay	3.05	16.54	3.17	16.11
	(1.73)	(4.08)	(.65)	(3.65)
Sweetgum	2.34	12.96	3.08	15.86
	(.35)	(2.18)	(.49)	(2.01)
Tupelo, black	3.20	11.99	3.96	17.73
	(.64)	(2.58)	(.92)	(2.72)
Yellow-poplar	2.51	18.45	3.44	19.53
	(.35)	(3.65)	(.50)	(2.57)

---

[1] Values for wood or bark ground to pass a 40-mesh screen, and extracted with an alcohol-benzene solution followed by a final extraction with ethanol. Percentage of unextracted ovendry weight; see table 3-1 for description of trees sampled.

[2] The first value tabulated under each heading is the average value for 10 trees; below (in parentheses) is the within-species standard deviation.

[3] Manwiller, F.G. Unpublished data in Final Report FS-SO-3201-1.41, dated March 19, 1981, U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Pineville, La.

[4] From a point 6 inches above ground level, to the point where the central stem could no longer be distinguished, or to a 0.5-inch minimum diameter outside bark.

[5] From the point of juncture with central stem extending out to a branch diameter of 0.5 inch outside bark.

[6] Mostly sugarberry.

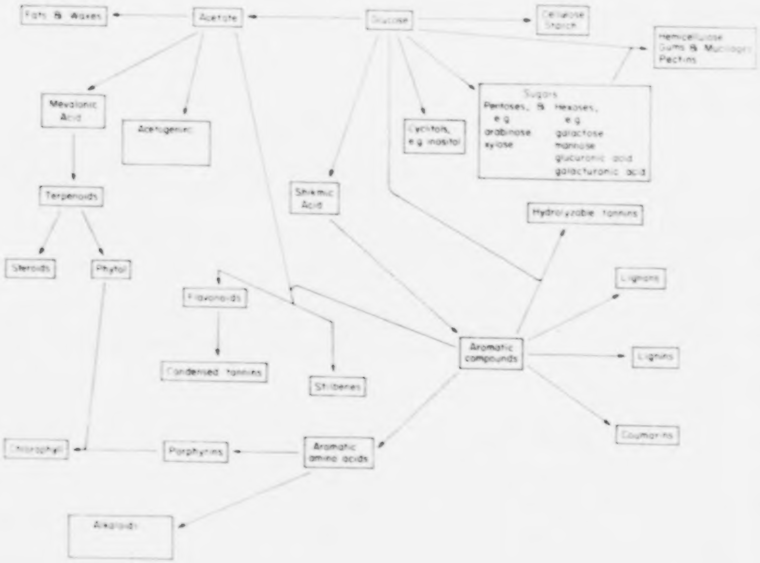
SOURCES AND CLASSES

Extractives include compounds involved in a tree's metabolic process, and artifacts from external sources or from further modification of metabolites by non-metabolic processes.

The extractives formed from a tree's metabolic processes may be primary or secondary metabolites. The **primary metabolites** are the bio-organic intermediates common to essentially all organisms. Thus most primary metabolites can be interconverted in the organism into the other primary metabolites via the intermediary metabolic processes.

Typical primary metabolites include simple sugars, amino acids, simple fats, various carboxylic acids, and others. These will always be found among the extractives of living trees, although the amounts will vary depending on the time in the growth cycle, the nutritional state, the tissue, and the season. Reports of isolation of these metabolites are of little taxonomic significance.

Secondary metabolites are generally compounds more complex than the primary; taxonomic distribution is restricted and their formation within the organism is essentially irreversible. Thus secondary metabolites express individuality of a species in chemical terms. Figure 6-11 illustrates the general secondary pathways that bring about this type of extractives in eastern hardwoods. Glucose, typically the primary product of photosynthesis, is the starting material for producing both cell wall components and most secondary metabolites.


Fats & Waxes
Acetate
Glucose
Cellulose
Starch
Hemicellulose
Gums & Mucilages
Pectins
Mevalonic Acid
Acetogenic
Cyclitols, e.g. inositol
Sugars
Pentoses, & Hexoses,
e.g.
arabinose
xylose
e.g.
galactose
mannose
glucuronic acid
galacturonic acid
Terpenoids
Shikimic Acid
Hydrolyzable tannins
Steroids
Phytol
Flavonoids
Lignans
Aromatic compounds
Lignins
Condensed tannins
Stilbenes
Coumarins
Chlorophyll
Porphyrins
Aromatic amino acids
Alkaloids

M 146 188

Figure 6-11.—Generalized biosynthetic pathways. (Drawing after Rowe and Conner 1979.)

Certain secondary metabolites are apparently ubiquitous to hardwoods and in the context of this review are not taxonomically significant. These include starch, sitosterol, simple terpenoids, chlorophyll, phenylpropanoids, the common flavonoids, simple tannins, and probably compounds such as scopoletin that are mentioned repeatedly throughout this review. All hardwoods thus possess the enzymes necessary for producing these largely intermediate compounds. In some species or tissues these intermediates accumulate in pools that can be isolated in large quantities, whereas in others they are metabolized further as fast as they are formed, thus are isolated with difficulty, in only small amounts. Further, these pools of intermediates may be limited to specific tissues or by specific conditions; this accounts for their variability.

Many secondary metabolites have a more restricted distribution than do the primary because not all biogenetic pathways are operative in all species or tissues and they may terminate at different stages. These metabolites may be characteristic of any taxonomic grouping, from a family to a chemical race within a species. They form the basis for chemotaxonomy because they reflect in part the enzyme systems that produced them, thus the genetic makeup of a tree. However, the expression of these enzymes may be controlled by environmental factors including season, nutritional state, or particular tissues; attack by certain decay organisms may stimulate wound response reactions in some taxa. Thus chemotaxonomic studies based on the relative amounts of various metabolites can be highly misleading if the sample is insufficient to warrant statistical treatment.

Chemically, many of these secondary metabolites are end products of metabolism, and more elaborate and complex than those common to all hardwoods. Such extractives occurring in pine-site hardwoods include alkaloids (magnolias, yellow-poplar), sesquiterpenes (yellow-poplar, elms), acetogenins (hickories), complex coumarins (sugar maple), and lignans (magnolias, elms, oaks).

Aromatic compounds are formed biogenetically either from acetate via malonyl CoA to give the aromatic "acetogenins" or directly from glucose via the shikimic acid pathway. In some instances, e.g., the flavonoids and stilbenes, different parts of the same molecule are derived via both pathways. Figure 6-12 shows the biogenesis of simple aromatic compounds via the shikimic acid pathway and their conversion into lignin and the other common phenolic extractives obtained from eastern hardwoods—hydrolyzable and condensed tannins, flavonoids, coumarins, and lignans. The coumarins and their glycosides apparently are important in regulating the enzymes in a tree (Hoover et al. 1977).

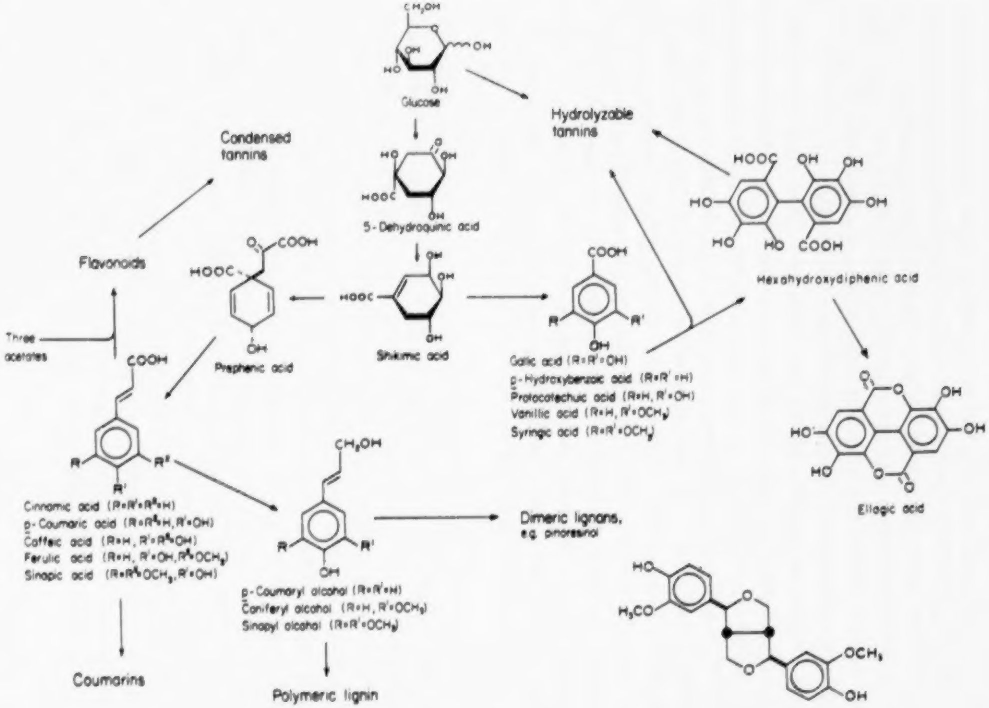

Glucose
5-Dehydroquinic acid
Shikimic acid
Prephenic acid
Hydrolyzable tannins
Condensed tannins
Flavonoids
Three acetates
Gallic acid (R=R'=OH)
p-Hydroxybenzoic acid (R=R'=H)
Protocatechuic acid (R=H, R'=OH)
Vanillic acid (R=H, R'=OCH3)
Syringic acid (R=R'=OCH3)
Hexahydroxydiphenic acid
Ellagic acid
Cinnamic acid (R=R'=R''=H)
p-Coumaric acid (R=R''=H, R'=OH)
Caffeic acid (R=H, R'=R''=OH)
Ferulic acid (R=H, R'=OH, R''=OCH3)
Sinapic acid (R=R''=OCH3, R'=OH)
p-Coumaryl alcohol (R=R'=H)
Coniferyl alcohol (R=H, R'=OCH3)
Sinapyl alcohol (R=R'=OCH3)
Dimeric lignans, e.g. pinoresinol
Coumarins
Polymeric lignin

Figure 6-12.—Aromatic compounds derived from glucose. (Drawing after Rowe and Conner 1979.)

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Tannins are used in the leather industry for converting animal skins into stable leather by their ability to form multiple hydrogen bonds with proteins. Most water-soluble polyphenols in the molecular weight range 500 to 3,000 have this property. Because tannins are capable of precipitating enzymes they can detoxify microbial digestive enzymes as well as interfere with the activity of isolated plant organelles. They are markedly astringent and have been implicated in initiating esophageal cancer (Morton 1973). The early literature on tannins must be treated with caution. Tannin was often considered as the amount of hot-water extract if this extract was capable of precipitating gelatin or being precipitated by heavy metals, alkaloids, or acidified formaldehyde. Then the percentage of tannin was accompanied (although often was not) by the **percentage purity** of the tannin determined by the fraction of the hot-water extract absorbed by chromed hide powder.

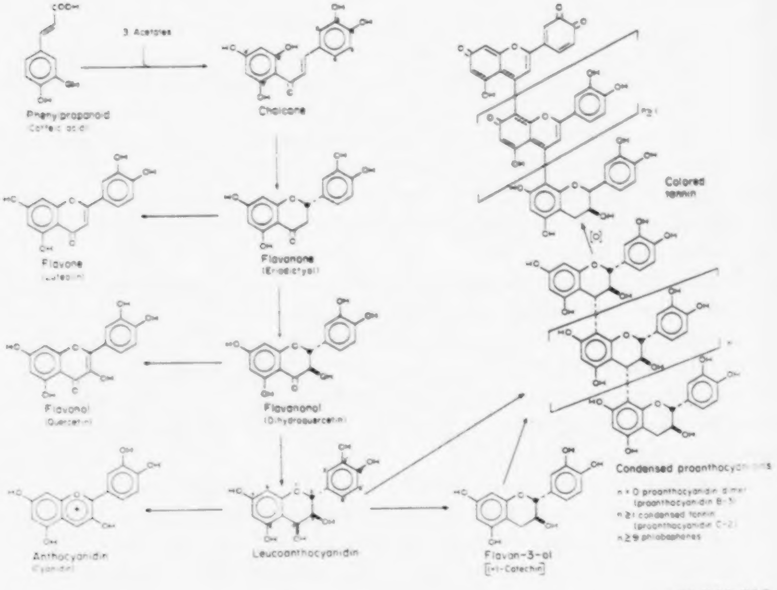
Vegetable tannins may be either hydrolyzable or condensed. **Hydrolyzable tannins** contain a polyhydric alcohol, predominantly glucose, partially or wholly esterified with gallic acid, hexahydroxydiphenic acid, and their derivatives. Tannins with this type of structure can be readily hydrolyzed by acids or enzymes to give the carbohydrate moiety and the phenolic acid moieties such as gallic acid and ellagic acid (the dilactone of hexahydroxydiphenic acid). Therefore these tannins are also called gallotannins or ellagitannins.

Condensed tannins are flavonoid polymers that contain only phenolic moieties and give no significant amounts of low-molecular-weight compounds on hydrolysis. These tannins instead tend to polymerize further in acid solution to give insoluble, amorphous, colored phlobaphenes. Figure 6-13 outlines the general biogenetic interrelationships among the various types of flavonoids and the condensed tannins. The precise biosynthetic pathways have not been fully elucidated (Haslam 1977). The interrelationships are illustrated by the quercetin oxidation pattern that apparently is the most common although many other hydroxylation patterns are known. Quercetin, a common extractive from hardwoods, and related compounds were recently shown to have mutagenic activity (Bjeldanes and Chang 1977).

O- and *C*-glycosylated flavonoids are also found in the eastern hardwoods as are a variety of methyl ethers and a few alkyl derivatives. The anthocyanins (the glycosylated derivatives of the anthocyanidins) contribute to the beautiful colors of autumn leaves of hardwoods (Hass 1977). The leucoanthocyanidins also occur as glycosylated derivatives, the leucoanthocyanins. The leucoanthocyanins (leucoanthocyanidins) are colorless precursors of the anthocyanins (anthocyanidins).

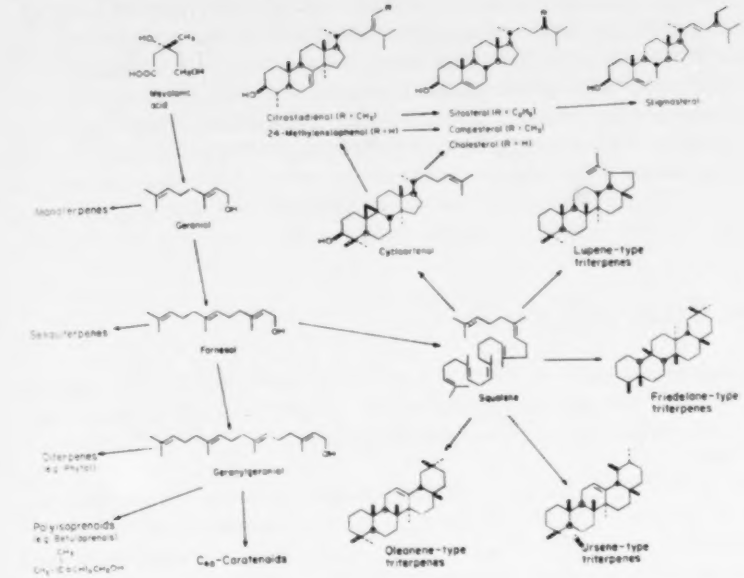
The flavan-3,4-diol (leucoanthocyanidin) and flavan-3-ol precursors of the condensed tannins polymerize first into a wide variety of dimeric and trimeric proanthocyanidins (Bate-Smith 1975, Haslam 1977, Haslam et al. 1977, Thompson et al. 1972, Weinges et al. 1969) with different types of linkages between the flavonoid groups. The proanthocyanidins are predominately polymers of (+)-catechin and its 3-epimer (−)-epicatechin; as a result they yield cyanidin if treated with acid. Corresponding derivatives possessing a 3′, 4′, 5′-hydroxylation pattern [(+)-gallocatechin, (−)-epigallocatechin] yield the corresponding delphinidin on treatment with acid.

Catechin dimer (proanthocyanidin B-3) and trimer (proanthocyanidin C-2) are illustrated in figure 6-13. Further polymerization leads to higher oligomers (of flavan-3-4-diol and flavan 3-ol) principally responsible for the properties usually attributed to the true tannins. Eventually, polymerization leads to the high-molecular-weight phlobaphenes that are insoluble. Still higher molecular weight polymers, such as the red powder that drops out if laboratory corks are rolled to soften them, are probably the backbone on which suberin is laid in the formation of cork. Therefore, the cork fraction of bark consists of a three-dimensional network of insoluble polyflavonoids, together with polyestolide fats and waxes (suberin). Although largely insoluble in inert solvents, suberin can be dissolved by hot, dilute alkali to yield monomeric fatty and wax compounds, and a polyflavonoid "phenolic acid" that results from rearrangement of the flavonoid nucleus (Sears et al. 1974). Pure phenolic polymers are colorless, but the tannins found in nature are normally colored, presumably due to oxidation, to extended conjugated systems such as that sh own in figure 6-13, or to *o*-quinones. The condensed tannins and related polyflavonoids are extremely common extractives, especially in bark. Roux (1972) has written an excellent review of this subject and Harborne (1977) has discussed the relationship between flavonoids and the evolution of the angiosperms.


3 Acetates
Phenylpropanoid
(Caffeic acid)
Chalcone
Flavone
(Luteolin)
Flavanone
(Eriodictyol)
Flavonol
(Quercetin)
Flavanonol
(Dihydroquercetin)
Anthocyanidin
(Cyanidin)
Leucoanthocyanidin
Flavan-3-ol
[(+)-Catechin]
Colored tannin
[O]
Condensed proanthocyanidins
n = 0 proanthocyanidin dimer (proanthocyanidin B-3)
n ≥ 1 condensed tannin (proanthocyanidin C-2)
n ≥ 9 phlobaphenes

M 146 010

Figure 6-13.—Biosynthesis of flavonoids and condensed proanthocyanidins (condensed tannins). (Drawing after Rowe and Conner 1979.)


HOOC
CH₂OH
Mevalonic acid
Citrostadienol (R = CH₃)
24-Methylenelophenol (R = H)
Sitosterol (R = C₂H₅)
Campesterol (R = CH₃)
Cholesterol (R = H)
Stigmasterol
Monoterpenes
Geraniol
Cycloartenol
Lupene-type triterpenes
Sesquiterpenes
Farnesol
Squalene
Friedelane-type triterpenes
Diterpenes (e.g. Phytol)
Geranylgeraniol
Polyisoprenoids (e.g. Betulaprenols)
C₄₀-Carotenoids
Oleanene-type triterpenes
Ursene-type triterpenes

M 146 011

Figure 6-14.—Biosynthesis of steroids and terpenoids. (Drawing after Rowe and Conner 1979.)

Outlined in figure 6-14 are the general biosynthetic relationships of the compounds derived from acetate (i.e., acetyl CoA) via the intermediacy of mevalonic acid. These pathways are responsible for formation of the monoterpenes, sesquiterpenes, triterpenes, and steriods. Sterols (i.e., phytosterols) are ubiquitous in the plant kingdom. The most common of these is sitosterol (24-ethylcholesterol) that always co-occurs with lesser amounts of its lower homologs, campesterol and cholesterol, and minor amounts of their saturated counterparts, stigmastanol, campestanol, and cholestanol. The co-occurrence of these six sterols suggest that the hydrogenase enzyme that reduces the side-chain double bond is not completely stereospecific. In this review, β-sitosterol is taken to represent the sitosterol-rich mixture of sitosterol and campesterol, whereas γ-sitosterol is the campesterol-rich mixture of sitosterol and campesterol (Thompson et al. 1962). Various other sitosterols have been reported in early literature. α_1-Sitosterol has been shown identical to the triterpene citrostadienol (Bates et al. 1968) that is always accompanied by small amounts of its lower homolog, 24-methylenelophenol. The α_2- and α_3-sitosterols are now known to be mixtures rich in cycloartenol and its derivatives. Many other sterols are known that are intermediates between the initially formed cycloartenol and the last-formed sterol, stigmasterol, but in most cases these do not accumulate and are metabolized as rapidly as they are formed. Unlike the other sterols often found in the form of esters of fatty acids, stigmasterol usually is found predominantly unesterified.

Extractive artifacts can arise from many sources, none of which involves a tree's enzyme systems. Some may be metabolites of micro-organisms which can often be found in apparently sound wood. Some extractives from tree barks may be lichen metabolites. Most important are artifacts formed by autoxidation and nonenzymatic free radical or acid-catalyzed condensations. These reactions are particularly common among the polyphenolic heartwood extractives. Thus the color in tannins is probably predominantly an artifact. Low decay resistance of some central heartwoods may result from polymerization of toxic phenolics by the acidity from anaerobic bacterial attack.

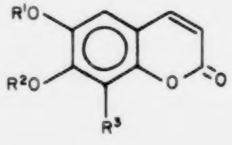
ASH, GREEN AND WHITE

Extractives content of white ash stemwood from Georgia and Tennessee averaged 5.4 and 6.3 percent, respectively; 4.0 and 3.3 percent, respectively, were phenolics; 1.2 and 2.3 percent carbohydrates; and 0.2 and 0.7 percent resin (table 6-7).

Stemwood of pine-site six-inch green and white ash sampled throughout these species' southern ranges averaged 6.23 and 6.09 percent extractives; that of branchwood averaged 7.46 and 7.51 percent (table 6-14). Stembark of these green and white ash trees averaged 17.57 and 17.02 percent extractives; that of branchbark 21.8 and 20.88 percent.

Russell et al. (1942-1945) found that the bark of white ash grown in the Southeast contains 4.5 to 4.8 percent tannin. Stachyose and especially mannitol are characteristic sugars found in *Fraxinus* species (Oesch 1969; Plouvier 1954).

Coumarins (fig. 6-15), flavonoids, simple phenolics, and their glycosides are also characteristic extractives of *Fraxinus* species. Coumarin derivatives are responsible for the blue to blue-green florescence of water extract of the bark. Glycosides have been implicated as the active antibiotic substances found in barks of green and white ash (Jung and Hubbes 1965).

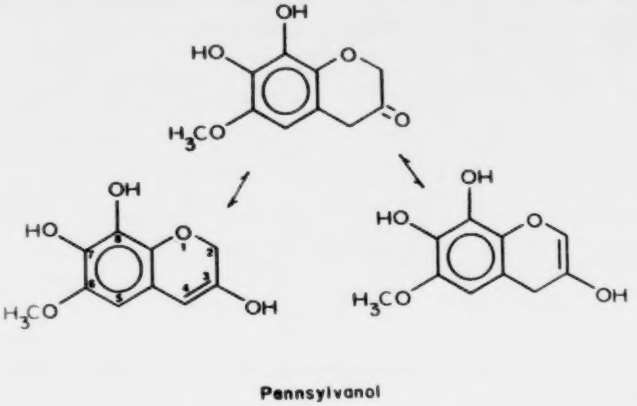


	R^1	R^2	R^3
Esculetin	H	H	H
Esculin	Glucose	H	H
Scopoletin	CH_3	H	H
Scopolin	CH_3	Glucose	H
Fraxetin	CH_3	H	OH
Fraxin	CH_3	H	$\underline{O}$-Glucose

M 146 170

Figure 6-15.—Some natural coumarins. (Drawing after Rowe and Conner 1979.)

In addition to these entities, the bark of green and white ash contains syringoside and fraxin (Plouvier 1952, 1954). The novel chromenol pennsylvanol has been isolated from the bark of green ash; data obtained on the purified compound are best explained if pennsylvanol exists as a mixture of tautomers as shown in figure 6-16 (Venkateraman 1977).



M 146 190

Figure 6-16.—Pennsylvanol. (Drawing after Rowe and Conner 1979.)

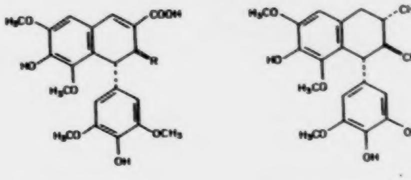
Medicinal uses and effects.—The bark of white ash has been used in folk medicine as a diuretic, in a tonic, and to relieve fever (Krochmal et al. 1969). A lichen (*Lecanora conizaeoides*) growing on the bark of a *Fraxinus* species caused dermatitis on a woodcutter's wife who developed it from contact with her husband's work clothes (Woods and Calnan 1976).

ELM, AMERICAN AND WINGED

Average extractives content of American elm stemwood from Georgia and Tennessee varied from 1.9 to 4.6 percent, of which 0.4 to 2.9 percent was phenolics, 0.8 to 1.5 percent carbohydrates, and 0.2 to 0.3 percent resin (table 6-7).

Stemwood of six-inch pine-site American and winged elm sampled throughout these species' southern ranges averaged 4.20 and 4.04 percent extractives; that of branchwood averaged 5.07 and 5.57 percent (table 6-14). Stembark of these American and winged-elm trees averaged 12.40 and 14.18 percent extractives; that of branchbark 15.78 and 14.87 percent.

Elm wood extractives have been reviewed by Levitin (1970) and Hegnauer (1964-1973), and chemical composition of elm bark has been studied by Chang and Mitchell (1955). Characteristic compounds thus far isolated include a mucilage from the bark, flavonoids, tannins, lignans (fig. 6-17 and table 6-15), aromatic sesquiterpenes (fig. 6-18 and table 6-16), sterols, and triterpenes. Although review of the literature does not indicate significant amounts of tannin in Southeastern elm species (Russell et al. 1942-1945), the bark of the elms has been used as a source of dyes and tannin (Mell 1939).

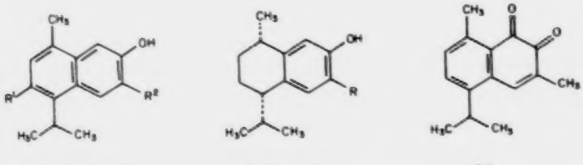


(1) R = CH_2OH
(2) R = COOH

(3) R = H
(4) R = rhamnoside

M 146 186

Figure 6-17.—Lignans in Ulmus heartwood; see also table 6-15. (Drawing after Rowe and Conner 1979.)



(1) R^1 = H, R^2 = COH
(2) R^1 = CH_3O, R^2 = CHO
(3) R^1 = H, R^2 = CH_3

(4) R = CHO
(5) R = CH_3

(6)

M 146 187

Figure 6-18.—Sesquiterpenes from Ulmus heartwood; see also table 6-16. (Drawing after Rowe and Conner 1979.)

Furniture manufacturers have repeatedly experienced difficulties with a yellow-colored stain in their finishes on *Ulmus rubra* wood. This yellow color will even migrate into vinyl plastic overlays. The compound responsible for the yellow discoloration is the lipophilic sesquiterpene, 7-hydroxycadalenal. This compound is accompanied by a series of related sesquiterpenes, 7-hydroxy-3-methoxycadalenal, 7-hydroxycadalene, and (-)-7-hydroxycalamenenal (Frachebound et al. 1968). The yellow stain is deepest in outer heartwood. Bleaching the wood with peroxide oxidizes the yellow sesquiterpene found at the wood surface to a colorless compound. However, because of the slight volatility of the sesquiterpene, the yellow stain returns as sesquiterpene slowly migrates from the interior of the wood to the wood surface.

7-Hydroxycalamenene first isolated from *U. thomasii* (Rowe and Toda 1969) apparently is ubiquitous in elm heartwood (Rowe et al. 1972). Mansonone *C* has also been detected in heartwood of various elms (Rowe et al. 1972).

TABLE 6-15.—*Lignans in Ulmus heartwood* (Rowe and Conner 1979)

Compound[1]	*Ulmus* species[2]					
	Alata	*Americana*	*Crassifolia*	*Rubra*	*Serotina*	*Thomasii*
Thomasic acid (1)	+	−	±	−	+	+ + +
Thomasidioic acid (2)	+	−	−	−	±	+
Lyoniresinol (3)	±	−	±	−	+	+ + +
(+)−Lyoniresinol-2a-*O*-rhamnoside (4)	+	−	+	−	+ +	+ +

[1] Numbers in parentheses refer to structures similarly identified in figure 6-17.
[2] −, not detected; ±, possibly minute amounts; +, small amounts, + +, moderate amounts; + + +, major amounts.

TABLE 6-16.—*Sesquiterpenes in Ulmus heartwood* (Rowe and Conner 1979)

Compound[1]	*Ulmus* species[2]					
	Alata	*Americana*	*Crassifolia*	*Rubra*	*Serotina*	*Thomasii*
7-Hydroxycadalenal (1)	−	−	±	+ + +	−	−
7-Hydroxy-3-methoxycadalenal (2)	−	−	−	+	−	−
7-Hydroxycadalene (3)	−	+	−	+	−	±
(−)-7-Hydroxycalamenenal (4)	±	−	±	+ +	−	−
(−)-7-Hydroxycalamenene (5)	+ +	+ + +	+ +	+	+ +	+ + +
Mansonone *C* (6)	−	+ +	±	−	+	±

[1] Numbers in parentheses refer to structures similarly identified in figure 6-18.
[2] −, not detected; ±, possibly minute amounts; +, small amounts, + +, moderate amounts; + + +, major amounts.

7-Hydroxycalamene and 7-hydroxcadalene were found toxic to many microorganisms and are produced in American elm in response to wounding (Balsillie 1972). The total phenolic content among the various elm species can apparently be correlated with their susceptibility to Dutch elm disease (Rowe et al. 1972).

The free sterols in American elm contain sitosterol and campesterol (Rowe et al. 1972).

The extractives in the bark of American elm have been investigated with particular emphasis on Dutch elm disease. Thus lupcyl cerotate and catechin-7-β-D-xylopyranoside (Doskotch et al. 197C,1973) as well as friedelan-3β-ol (Baker and Norris 1967) have been reported to stimulate feeding of the smaller European elm bark beetle. Interestingly, juglone, which can be isolated from shagbark hickory, as well as other napthoquinones deter bark beetles from feeding (Gilbert et al. 1967; Norris 1969, 1970). Chemical deterrents to elm bark beetle feeding have also been found in another nonhost tree, white oak (Gilbert and Norris 1968).

The elm bark beetle aggregation pheromone is composed of three components: (−)-4-Methyl-3-heptanol; 2-*endo*, 4-*endo*-dimethyl-5-ethyl-6,8-dioxabicyclo(3.2.1)octane (multistriatin); and (−)-α-cubebene (Pearce et al. 1975). α-Cubebene is a naturally occurring sesquiterpene in elm bark. Structurally multistriatin, the synthesis of which has been reported. (Cernigliaro and Kocienski 1977), is closely related to frontalin, an aggregating pheromone of the southern pine beetle (Mundy et al. 1971), and brevicomin, the principle component of the western pine beetle pheromone (Bellas et al. 1969). Bait tests with a mixture of the synthetic pheromones of the elm bark beetle (multilur) have been successful in Europe (Vite et al. 1976).

HACKBERRY

Stemwood of six-inch pine-site hackberry (mostly sugarberry) sampled throughout the species' southern range averaged 5.53 percent extractives; branchwood of these trees averaged 6.66 percent extractives (table 6-14). Stembark and branchbark of these trees averaged 7.97 and 10.61 percent extractives.

The extractives chemistry of *Celtis* species has not been studied in detail. Preliminary work showed that wood and bark of sugarberry were almost devoid of phenolic extractives; only triterpenoid acids, fatty acids, and glucose were detected (Seshadri 1973).

HICKORY

Average extractives content of pignut and mockernut hickory stemwood from Georgia and Tennessee varied from 3.4 to 9.0 percent; of this content, phenolics constituted more than half, carbohydrates about one-third, and resin less than one-tenth (table 6-7). Bark of these hickories from Georgia and Tennessee had a total extractives content of 18.32 percent comprised as follows: wax 1.61 percent, phenols 2.15 percent, tannins and sugar 10.71 percent, and polymeric carbohydrates 3.85 percent (Hergert et al.[1]).

Stemwood and branchwood of six-inch pine-site hickory trees (*Carya* sp.) sampled throughout their southern range averaged 5.35 and 6.31 percent extractives (table 6-14). Stembark and branchbark of these trees averaged 18.01 and 18.89 percent extractives.

Extractives of hickory bark and wood have not been intensively investigated. Chemistry of the Juglandaceae family has been reviewed by Farnsworth et al. (1969-1974) and Fieser and Fieser (1959). Mitchell (1955) reported on the chemistry of hickory species inclusive of pecan.

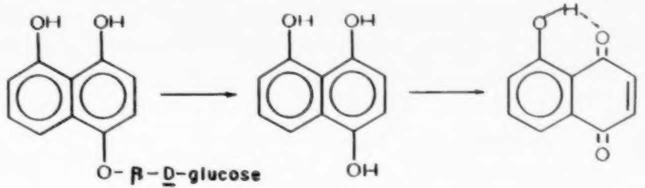
Tannin content of hickory and pecan barks were reported by Russell et al. (1942-1945) as follows:

Hickory species	Percent
Bitternut	7.8
Mockernut	Insignificant to 5.0-9.8
Pignut	7.6-10.0
Sand	6.7
Shagbark	0
Shellbark	4.7, 6.7
Pecan	5.7

All of the wood (*Carya* spp.) was reported as not containing tannin, although young whole pecan plants contain 11.5 percent tannin (Happich et al. 1954). It is intriguing that in a survey of the general chemistry of pecan bark, the benzene-extracted bark had an extraordinarily large amount of ethanol extract, 18.1 percent (Chang and Mitchell 1955). Pecan bark contains azaleatin (quercetin 5-methyl ether) and the flavonol caryatin (quercetin 3,5-dimethyl ether) (Sasaki 1964)) and juglone.

Medicinal uses and effects.—The occurrence of juglone apparently is characteristic of the barks (especially the husks) of the *Juglandaceae* family, and probably explains both the use of pecan bark by Mexican Indians to stupefy fish (Pennington 1958) and of hickory bark to repel insects. Juglone is also a purgative (Krochmal et al. 1969). Juglone can cause blackening, blistering, and peeling of the skin; is a tranquilizer and sedative (Bhargava 1967; Westfall et al. 1961); has antitumor activity (Bhargava and Westfall 1968); is fungitoxic and an antibiotic; and is allelophathic (Soderquist 1973). Unquestionably, this is a significant compound.

Juglone or a precursor is probably the active substance responsible for dermatitis from the nutshells, roots, and bark of black walnut (*Juglans nigra* L.). Juglone has not been reported in the wood and no cases of skin or mucosal irritation by the wood have been found (Woods and Calnan 1976). Juglone is formed in a tree from dihydrojuglone-4-glucoside via dihydrojuglone (fig. 6-19) and readily polymerizes to brown-black pigments. Apparently it is part of the wound response mechanism, although it is not reported in the wood.



Dihydrojuglone - 4 - glucoside Dihydrojuglone Juglone

M 146 167

Figure 6-19.—Formation of juglone. (Drawing after Rowe and Conner 1979.)

MAPLE, RED

Extractives content of red maple stemwood from Georgia and Tennessee averaged 8.6 and 5.3 percent; more than half this content was phenolics (6.3 and 3.0 percent). Stemwood of 6-inch pine-site red maples sampled throughout the species' southern range averaged 3.84 percent extractives; that of branchwood averaged 4.12 percent (table 6-14). Stembark and branchbark of these 6-inch trees averaged 16.36 and 18.66 percent extractives.

Chemistry of the family Aceraceae has been summarized to 1961 by Hegnauer (1964-1973) and further reviewed by Levitin (1970).

The maples, especially black maple (*Acer nigrum* Michx. f.) and sugar maple (*A. saccharum* Marsh.), and to a lesser extent red maple and silver maple (*A. saccharinum* L.), are best known for the maple syrup produced by boiling down their sap (Willits 1965).

Maple sap consists primarily of sucrose and arabinogalactan (Adams and Bishop 1960). Other constituents include quebrachitol (2-*0*-methyl-inositol) (Oesch 1969; Stinson et al. 1967), phytokinins (Nitsch and Nitsch 1965), two trisaccharides (Haq and Adams 1961), glucose, fructose, allantoin, allantoic acid, vanillin, vanillic acid, syringaldehyde, coumarin, malic acid, coniferyl alcohol, coniferaldehyde, and guaiacol. Quebrachitol is apparently ubiquitous in the Aceraceae (Hegnauer 1964-1973).

Tannins are not present in red maple wood, although tannin content of the bark is 6.9 percent (Russell et al. 1942-1945).

Gallic acid and catechin are the main phenolics in the clear wood of red maple (Tattar and Rich 1973). Significantly, these are both absent in discolored or decayed wood. The color cannot be completely extracted from discolored red maple; presumably the phenolics present have been oxidatively polymerized.

Red maple wood and bark have been found to contain glucose, β-sitosterol, **D**-catechin, and a procyanidin consisting of leucocyanidin units linked 4-8 (Narayanan and Seshadri 1969; Seshadri 1973). However, the procyanidin from the wood was a dimer, whereas that from the bark was a trimer. The bark also contains pyrogallol and gallic acid.

Medicinal uses and effects.—The bark of red maple is used in folk medicine as an anthelmintic, tonic, and opthalmiatric (Krochmal et al. 1969). Maple-bark disease is a pulmonary hypersensitivity reaction to the fungus *Cryptostroma corticale*; it is marked by cough, night sweats, and radiographic evidence of infiltration (Woods and Calnan 1976).

OAKS

Average extractives content of stemwood of nine species of oak important on pine sites, sampled in Georgia and Tennessee, varied from 4.3 percent in water oak to 9.6 percent in one sample of southern red oak; about half of this content was phenolics, about one-tenth was resin, and the balance was carbohydrates (table 6-7). Of the minor oaks sampled, stemwood of live oak had most (13.2 percent) extractives (table 6-8).

Stemwood of six-inch pine-site oaks of 11 species sampled throughout their southern ranged averaged 5.58 percent extractives; extractives content of branchwood from these trees averaged 6.19 percent. Variation among species was substantial (table 6-14). Stembark and branchbark of these 11 species averaged 13.96 and 15.96 percent extractives.

Tannins.—Oaks are well known for the tannins isolated predominantly from their bark (Hathway 1958, 1959; Russell et al. 1942-1945). Values for the tannin content of the oaks compiled from various sources are given in table 6-17. Chestnut oak bark is known to be a satisfactory source of tannin. Blackjack, southern red, and black oak barks apparently have commercial potential (Beebe et al. 1953). Although any tannin content above 8 percent suggests commercial potential, various other factors must be considered. Purity of the tannins, stability of the solutions, color of the resultant leather, and reactivity with formaldehyde (for use in adhesives) affect commercial potential. The yield may be considerably increased if extraction is with aqueous sodium sulfite (Ekimova et al. 1964). This results in part from sulfonation, which increases solubility, and in part from the alkaline degradation of the high-molecular-weight polymeric flavonoids in cork to soluble so-called bark phenolic acids. The mechanism of this degradation has been elegantly elucidated (Sears et al. 1974). Oak is not now a commercial source of tannin in the United States. The last significant domestic production of tannin was from the American chestnut (*Castanea dentata* (Marsh.) Borkh.), which has been almost exterminated by chestnut blight.

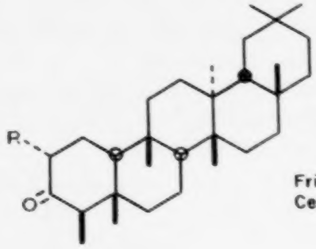
TABLE 6-17.—*Tannin content of wood and bark from 11 oak species frequently found on southern pine sites* (After Rowe and Conner 1979)

		Bark	
Oak species	Wood[1]	Reported averages and ranges	Purity
	Percent		
Black	I	5.6, 8.4, 6-12	
		9.2, 9.3	58
Blackjack	I	7.7, 8.8-9.2	64
Chestnut	3.3	6.25, 7.2-11.1	—
	—	10.8, 10-12, 8-14, 15.3-16.0	63
Laurel	I		—
Northern red	1.8, 2.5	4.6, 5.5, 5.4-11.1	
		10.9, 5.4-6.4	53
Post	2.9, 5.4	2.3, 3.1, 7.1-7.4	59
Scarlet	0	6.6, 6-8, 7.7, 7.1-10.6	58
Shumard	0, 3, 1	4.3, 5.2	—
Southern red	0, 1.8, 2.0	6.4-8.7, 8.6, 10.0, 9.7-9.9	67
Water	1.0	4.3, 4.6, 7-8	—
White	2.7	2.3, 6, 6.3, 5.1-7.2, 7, 7.9, 6.1-6.6	57

[1] I means: insignificant, i.e., less than 1 percent.

Oak barks contain **D**-catechin and **D**-gallocatechin, leucopelargonidin, leucocyanidin, leucodelphinidin, gallic acid, and various condensed tannins based on catechin-gallocatechin polymers. The structures of seven different dimers in European oak bark have been elucidated, as more recently has the structure of a catechin trimer (fig. 6-13) (Ahn 1974). Compounds such as these are probably common in all barks containing condensed tannins. In contrast to the condensed tannins that predominate in the bark, hydrolyzable tannins predominate in oak wood. The gallotannins and the ellagitannins isolated from European oak have been extensively studied, and many individual strucutures determined (Mayer et al. 1971). The series of natural products most difficult to study among eastern hardwood extractives are the complex mixture of individual condensed tannins in the bark and the individual hydrolyzable tannins in the wood.

Cork.—Commercially cork is derived primarily from the bark of the Mediterranean cork oak, *Q. suber*, grown slowly on dry poor soils. The innumerable studies on this complex of highly polymerized flavonoids and estolide waxes have been reviewed (Cooke 1961; Lanuza 1964). Cork is the original source of the pentacyclic triterpenes, friedelin and cerin (fig. 6-20), and oak barks have been found to contain more than 12 triterpenes with friedelane, glutinane, ursane, oleanane, lupane, and dammarane skeletons. Also common are various soluble waxy components, sterols, and esters such as lignoceryl ferulate.



Friedelin (R = H)
Cerin (R = OH)

M 146 171

Figure 6-20.—Oak triterpenes. (Drawing after Rowe and Conner 1979.)

Gluability.—Old (extractive-rich) oak bonds relatively poorly with phenol-formaldehyde adhesives. Water, or even more efficient, sodium carbonate extraction, has removed interfering materials. Since the addition of extra sodium hydroxide improves bonding, the deleterious effect may be predominately caused by acidity of the extractives (Roffael and Rauch 1974).

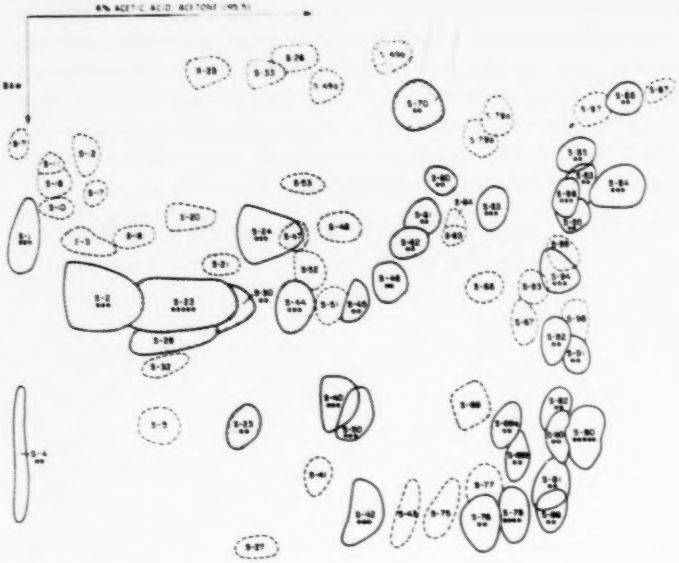
Medicinal uses and effects.—The oak bark formerly used for internal and external pharmaceutical purposes was that of white oak. Because the bark contains tannins, it has been used as an astringent and an antiseptic. The European drug **Cortex *Quercus*** is the astringent extract of oak inner bark. A bark tea is used in Appalachia to treat burns and sore throat (Krochmal et al. 1969). Southern red oak bark has been used to treat dysentry, pulmonary and uterine hemorrhage, and intermittant fever (Morton 1973). A few cases of sensitivity to oak wood dust have been reported (Woods and Calnan 1976), but the allergen is unknown.

Black oak.—The inner bark of black oak contains the simple flavonoids, kaempferol, myricetin, and probably quercetin. An additional flavonoid found in this bark is quercitrin (quercetin 3-*o*-rhamnoside), which was extracted at one time for use as a yellow dye for wool and hair. These flavonoids apparently are common minor constituents of oak bark and wood. Bark of black oak, and other oaks, contains inositols such as quercitol, first found in cork oak (Plouvier 1964). The inhibitory substances in oak bark used for growing orchids have been identified as gallic acids and tannins (Frei 1972).

Northern red oak.—Northern red oak has been the most thoroughly investigated of the eastern oaks. The relationship between heartwood formation and phenolic extractives has been examined (Nelson 1975). The extractives were shown to contribute to the dimensional stability of the wood (Shim 1954). Figure 6-21 shows the result of a two-dimensional paper chromatogram of the sapwood and the heartwood acetone-water (95:5) extractives (Seikel et al. 1971). The contrast between the components of the sapwood and the heartwood is particularly noteworthy. Hydrolyzable gallotannins such as hamamelitannin [5-galloyl-2-(galloylhydroxymethyl)-ribofuranose] and ellagitannins predominate, and are also the main components in the more polar acetone-water (1:1) and water extracts. In addition to the compounds listed, the sapwood contains leucoanthocyanins and possibly pinoresinol (fig. 6-12). *m*-Digallic acid apparently is present in both the heartwood and the sapwood, but surprisingly gallocatechin was absent. The most interesting components in addition to the tannins are the coumarin, scopoletin (fig. 6-15) and the lignans, syringaresinol (see also yellow-poplar), lyoniresinol, and lyoniside (fig. 6-22). 2,6-Dimethoxybenzoquinone is probably formed by free radical oxidation of syringyllignans. Neither flavonols nor their glycosides could be detected. However, color tests suggest that several esters of hydroxycinnamic, vanillic, and syringic acids were present as well as glucosides, arabinosides, and xylosides. The inner bark was very different from either the sapwood or the heartwood. Although no gallic or ellagic acids were present, tannin esters, catechin, flavonoids, and lyoniside were tentatively identified. The general chemistry of this bark has been studied (Chang and Mitchell 1955), as has that of chestnut oak (Binotto and Murphy 1975). Tartaric acid has been suggested as the cause of toxicity of northern red, black, northern pin (*Q. palustris* Muenchh.), and bur oak (*Q. macrocarpa* Michx.) heartwood extracts against oak wilt fungus (Bilbruck 1959).

Northern red oak is a valuable commercial wood, but its value is often degraded by a variety of stains, most of which are due to the phenolics in the wood. Thus, contact of the wet wood with sources of iron such as spikes, concrete, steel wool, and other abrasives can lead to formation of blue-black iron tannates (Vick and Taras 1969). Fortunately, these are usually readily bleached with oxalic acid. Other stains develop from air oxidation of the phenolics in the wet wood, perhaps with the help of enzymes. These stains often can be prevented by high-temperature steaming. Extraordinarily high concentrations of heartwood phenols can cause other stains around defects and injuries in the wood. Still other stains result from microbiological attack or fall into the category of "mineral stains."

SAPWOOD


6% ACETIC ACID-ACETONE (95:5)
BAW
S-70
S-2
S-22
S-24
S-28
S-44
S-80

M 146 192

HEARTWOOD

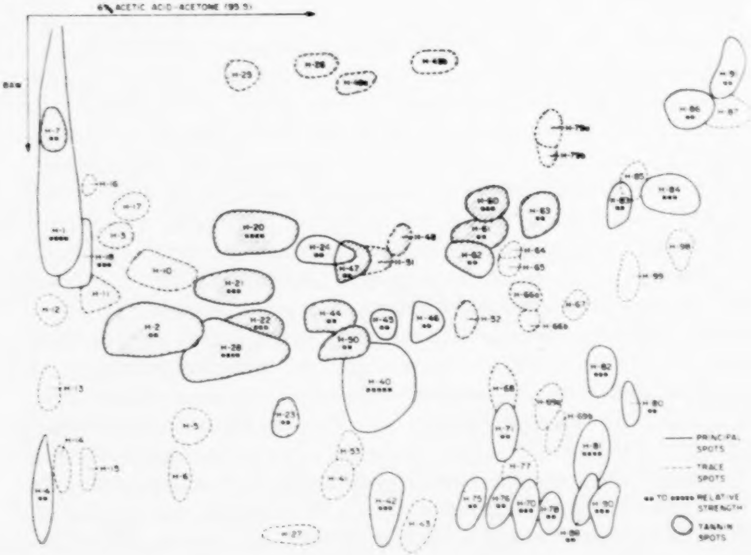

6% ACETIC ACID-ACETONE (95:5)
BAW
H-1
H-2
H-20
H-21
H-28
H-40
H-84
PRINCIPAL SPOTS
TRACE SPOTS
•• TO ••••• RELATIVE STRENGTH
TANNIN SPOTS

Figure 6-21.—Two dimensional paper chromatographs of acetone-water extracts of northern red oak wood. Elution in one direction was with 6% acetic acid-acetone (95-5), and in the other with butanol-acetic acid-water (BAW). Known compounds in numbered spots are tabulated below. (Drawing after Seikel et al. 1971.)

Spot No.[1]	Compound	Isolated from heartwood, H, and sapwood, S
1	Ellagic acid	H and S
20	Hamamelitannin	H and S
40	Gallic acid	H and S
42	Sinapaldehyde	H and S
43	Coniferaldehyde	H and S
50	Catechin	S
75	Scopoletin	H
76	Syringaldehyde	H and S
77	Propioguaiacone (propiovanillone)	H
78	Vanillin	H and S
80	Lyoniside	H and S
90	*rac*-Lyoniresinol	H
[2]	2,6-Dimethoxybenzoquinone	H
[2]	Resorcinol	H
[2]	Syringaresinol	H and S
[2]	p-Hydroxybenzaldehyde	S

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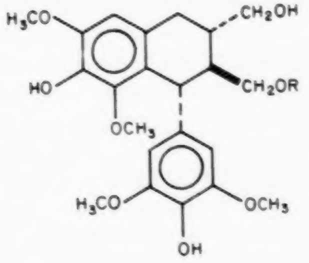
[1] Numbered spots, not tabulated, are unknown. Cross-hatched spots give positive color tests for tannins.

[2] Location on chromatograms unknown; probably masked under other spots.



Lyoniresinol (R = H)

Lyoniside (R = xyloside)

Lyoniresinol 2a-O-rhamnoside (R = rhamnoside)

M 146 169

Figure 6-22.—Oak lignans. (Drawing after Rowe and Conner 1979.)

A full understanding of the phenomena of stain development in oak wood will be attainable only when information on the chemistry of oak heartwood extractives has progressed considerably. However, catechin and gallocatechin moieties are undoubtedly involved because they are relatively easily oxidized to deeply colored quinones. The quinones can be bleached by reducing agents to the less colored hydroquinones or oxidatively bleached by cleavage of the quinoid ring. Because these bleaching agents are not completely successful in decolorizing stained oak wood, other factors must be involved such as different chemical chromophores or quinoid groups protected as insoluble complexes.

Water Oak.—Extractives content of water oak stemwood from Georgia averaged 4.3 percent comprised of 2.5 percent phenolics, 1.5 percent carbohydrates, and 0.3 percent resin (table 6-7).

Stem bark from these Georgia trees had 17.66 percent extractives content comprised as follows: wax 2.01 percent, phenols 0.38 percent, tannins and sugar 11.49 percent, and polymeric carbohydrates 3.78 percent (Hergert et al. [1]).

Stemwood of pine-site six-inch diameter water oak sampled through the species' southern range averaged 4.67 percent extractives content; that of branchwood averaged 5.60 percent (table 6-14). Stembark and branchbark of these trees averaged 11.28 and 14.50 percent extractives.

White oak.—The general chemistry of white oak (*Quercus alba* L.) bark has been investigated (Chang and Mitchell 1955) The heartwood was found to contain scopoletin (Baldwin et al. 1967); gallic and ellagic acids; gallotannins and ellagitannins; sitosterol; stigmasterol; campesterol; stigmastanol; lignoceryl ferulate and related esters; triglycerides of linoleic, oleic and palmitic acids; and coniferaldehyde (Chen 1970). Vanillin, syringaldehyde, and sinapaldehyde had been found earlier in the wood (Black et al. 1953). Coniferaldehyde and sinapaldehyde have also been reported in post oak wood; these simple phenolics are probably very common (Black et al. 1953). The corresponding ferulic and sinapic acids and salicylic and gentisic acids as well as pyrogallol, *p*-hydroxybenzaldehyde, eugenol, and *D*-mannitol have been reported in various foreign oaks. Many of the typical bark components have also been reported in the wood.

Wood of several species of the white oak group is used to make tight cooperage for whisky and wine; the extractives content of such barrels impart odor and flavor to their contents. Eugenol and two *Quercus* lactones (diastereoisomers of 3-methyl-4-octanolide) have been found in an unidentified member of this white oak group (Masuda and Nishimura 1971). The lactones were also found in aged whiskey and are responsible for its woody odor. Vanillin, syringaldehyde, and related phenolics derived from lignin also are important in the desirable odor contributed by oak barrels to whiskey and wine (Singleton 1974).

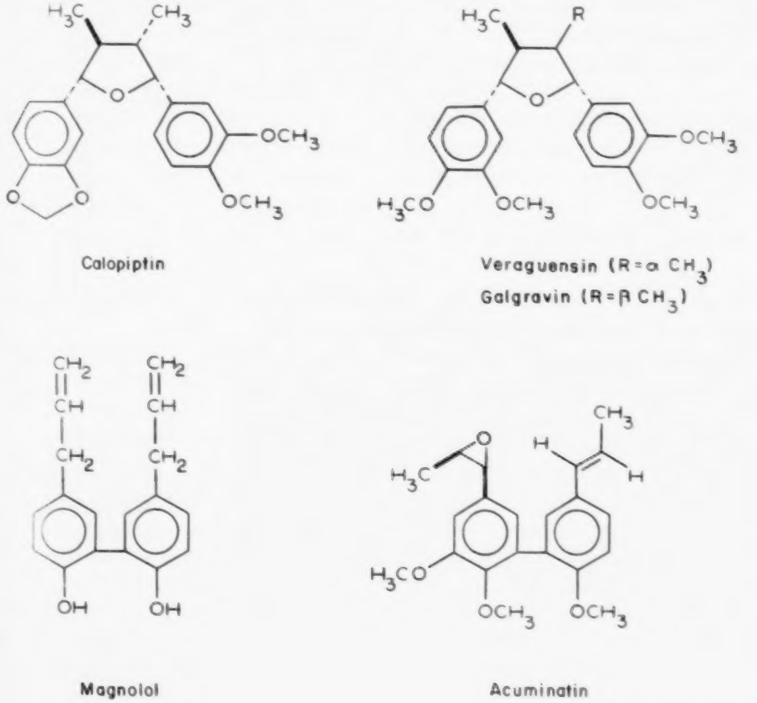
SWEETBAY

Extractives content of sweetbay stemwood from Georgia averaged 3.9 percent, of which 2.9 percent was phenolics, 0.9 percent carbohydrates, and 0.4 percent resin (table 6-7).

Stemwood of pine-site six-inch diameter sweetbay sampled through the species' southern range averaged 3.05 percent extractives; that of branchwood averaged 3.17 percent (table 6-14). Stembark and branchbark of these trees averaged 16.54 and 16.11 percent extractives.

Farnsworth et al. (1969-1974) and Hegnauer (1964-1973) have reviewed the chemistry of the Magnoleaceae family, which includes sweetbay and the magnolias. The extractives of magnolia wood and bark are characterized by lignans (fig. 6-23) and alkaloids, including those described under the sub-section on yellow-poplar, but also including alkaloids of the phenylethylamine, benzylisoquinoline, and bisbenzylisoquinoline types. Data on sweetbay extractives are limited to observation that they include small amounts of magnalol (Fujita et al. 1973), and that extracts of a cross between sweetbay and southern magnolia (*Magnolia grandiflora* L.) are inhibitory to both fungi and bacteria (Smale et al. 1964). Neither wood nor bark of sweetbay or southern magnolia contain significant tannin (Russell et al. 1942-1945).

Rowe and Conner (1979), after reviewing work on extractives of other eastern magnolias of this country and of Japanese magnolias, comment that the bark—especially that of branches—of eastern magnolias should perhaps be studied.



Calopiptin

Veraguensin (R = α CH_3)
Galgravin (R = β CH_3)

Magnolol

Acuminatin

M 146 180

Figure 6-23.—Lignans of magnolias. (Drawing after Rowe and Conner 1979.)

SWEETGUM

Average extractives content of sweetgum stemwood in Georgia was found to be less than 2 percent, with phenolics content of 0.2 percent or less; in contrast, sweetgum stemwood from Tennessee had 5.9 percent extractives comprised of 3.7 percent phenolics, 1.7 percent carbohydrates, and 0.5 percent resin (table 6-7).

Stemwood of 6-inch pine-site sweetgum sampled across the species' southern range averaged 2.34 percent extractives; extractives content of branchwood averaged 3.08 percent (table 6-14). Stembark and branchbark of these trees averaged 12.96 and 15.86 percent extractives.

Choong and Fogg (1976) reported the following extractives contents (percent) from four sweetgum trees sampled in eastern Louisiana—two from a bottomland site along the Mississippi River and two from an upland site (based on unextracted ovendry weight):

Tissue and solvent	Average	Standard deviation
Bark		
Ether	1.88	0.86
Ethanol	2.88	1.32
Hot Water	9.05	1.24
Sapwood		
Ether	.72	.41
Ethanol	.69	.44
Hot Water	1.79	.68
Heartwood		
Ether	1.05	.49
Ethanol	.86	.54
Hot Water	2.59	.49

Data from Isenberg et al. (1946, 1957) and Walkup et al. (1956) indicate that quantities of extractives in sweetgum wood are highly variable.

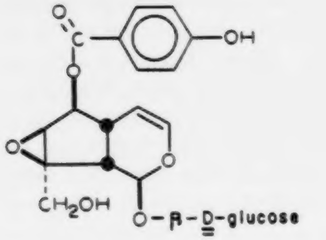
Storax.—Sweetgum is the source of an exudate known locally as sweet gum and commercially as American storax (or styrax); selling price in 1978 was just under $1.50 per pound. Although current production is small ($150,000/yr, Clark Co., Ala.), this was a significant industry during and after World War I (Gerry 1921; Mahood and Gerry 1921). American storax, essentially identical to Oriental storax from *Liquidambar orientalis* in Turkey, has been used in perfumery, chewing gum, incense, tobacco, adhesives, and pharmaceutical preparations as well as in folk medicine (Krochmal et al. 1969).

Storax is obtained by collecting the exudate from cuts made through the bark. Yields are up to 1 pound per tree per year, most of which is collected during the mid-June to mid-October growing period. Very little storax is stored in normal wood or bark. Apparently storax is formed in traumatic resin ducts near a wound. The most recent references (Crown 1962; Smith 1960) and a number of articles in the popular press have contained little scientific data. Surprisingly, no work has been reported on the chemistry of American storax since 1921, when even earlier work reporting the presence of cinnamyl cinnamate and related esters was confirmed (Guenther 1952). American storax is a true balsam. Oriental storax has been found to contain oleanolic, 3-epioleanolic (first time in nature), and oleanonic acids (Huneck 1963).

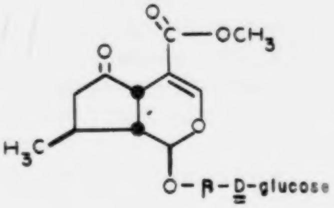
Sapwood and heartwood.—Sweetgum sapwood has been extensively studied and found to contain large amounts of vanillic and syringic acids plus 3,4-dihydroxyphenyl, galloyl, and related hydrolyzable tannins. Lesser components included vanillin, syringaldehyde, coniferaldehyde, sinapaldehyde, *m*-coumaraldehyde, gallic acid, dihydroquercetin, glucose, fructose, and soluble lignin fragments (Kirk and Lundquist 1970; Spencer and Choong 1977). Ellagic acid plus related methyl ethers and glycosides are also indicated (Spencer and Choong 1977). Polymeric phenolic glycosides predominate and apparently in the heartwood are heavily polymerized and oxidized to colored nontannin polymers. The heartwood has recently been shown to contain quercetin (Spencer and Choong 1977). Ether extractives of sweetgum wood contain the usual fatty acids and esters as well as β-sitosterol (Walkup et al. 1956).

Bark.—Hergert et al.[1] found that sweetgum bark had extractives content of 11.69 percent of unextracted ovendry weight; these extractives were comprised of 1.30 percent wax, 0.14 percent phenols, 3.31 percent tannins and sugar, and 6.94 percent polymeric carbohydrates.

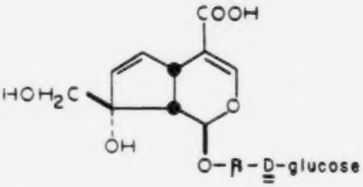
The general chemistry of sweetgum bark has been studied by Chang and Mitchell (1955). Successive extractions with benzene, 95 percent ethanol, hot water, and 1 percent sodium hydroxide dissolved 1.5 percent, 17.7 percent, 7.4 percent, and 21.3 percent, respectively. In contrast to the wood, which contains very little tannin, a content of 7.6 percent has been reported for the bark. Hot-water extracts of the bark produce large amounts of precipitate with gelatin or with formaldehyde-hydrochloric acid (Chang and Mitchell 1955). Hegnauer (1964-1973) reported Plouvier found that the bark contains 0.1 percent shikimic acid, and that both the wood and bark contain the monoterpene iridioside, monotropein (fig. 6-24) (Masaki et al. 1967). The phenolics in the bark apparently are closely related to those in the sapwood and include large amounts of gallic and ellagic acids plus 3,3′-di-*o*-methylellagic acid, other methylated ellagic acids, related glycosides, and ellagitannins and gallotannins (Nair and von Rudloff 1960). Although there are many similarities between the extractives of bark and sapwood, distributions of the individual components are different.



Catalposide



Cornin



Monotropein

M 146 166

Figure 6-24.—Iroid monoterpenes. (Drawing after Rowe and Conner 1979.)

Medicinal uses and effects.—In the early part of this century, an ether extract of sweetgum heartwood was reported to cause dermatitis (Sandermann and Barghoorn 1956; Woods and Calnan 1976); wood of the species, however, has not been reported to cause a problem.

The tannin-rich leaves of the sweetgum tree are still used today as a folk remedy to relieve sore throat and diarrhea, and the dry, spiny mature fruit is burned, and the ash applied to sores and burns (Morton 1973).

TUPELO, BLACK

Extractives content of black tupelo stemwood sampled in Georgia and Tennessee averaged 2.6 and 2.9 percent. Resin content was the same in wood from both states (0.3 percent); phenolics content of Georgia black tupelo wood was only 0.1 percent, whereas that from Tennessee had 1.2 percent. Carbohydrate contents were 2.2 and 1.4 percent (table 6-7).

Stem bark from the Georgia black tupelo trees had 17.05 percent extractives content comprised as follows: 2.12 percent wax, 0.09 percent phenols, 6.45 percent tannins and sugar, and 8.39 percent polymeric carbohydrates (Hergert et al.[1]).

Stemwood of six-inch pine-site black tupelo sampled through the species' southern range averaged 3.20 percent extractives content; that of branchwood averaged 3.96 percent (table 6-14). Stembark and branchbark of these trees averaged 11.99 and 17.73 percent extractives.

Although the general chemistry of black tupelo wood and bark have been investigated (Walkup et al. 1956; Chang and Mitchell 1955), no detailed studies have been conducted on extractives of this species. Neither the wood nor bark has significant tannin content. Preliminary work on the extractives of black tupelo heartwood indicates the presence of an alkaloid in minute amounts, phenolics, and one or more flavones (Venkateraman 1977). The ether extract of the prehydrolysis pulping liquors of black tupelo contained vanillic acid, syringic acid, vanillin, syringaldehyde, sinapaldehyde, and vanilloyl methyl ketone (Stanek 1958).

YELLOW-POPLAR

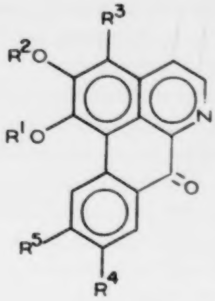
Extractives contents of stemwood of yellow-poplar from Tennessee averaged 2.4 percent, of which 1.4 percent was phenolics, 0.8 percent carbohydrates, and 0.2 percent resin (table 6-7).

Stemwood of pine-site six-inch yellow-poplar sampled through the species' southern range averaged 2.51 percent extractives content; that of branchwood averaged 3.44 percent (table 6-14). Stembark and branchbark of these trees averaged 18.45 and 19.53 percent extractives.

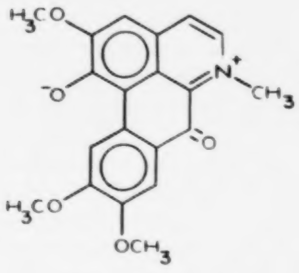
Reviews of the chemistry of yellow-poplar have been made by Farnsworth et al. (1969-1974), and Hegnauer (1964-1973). The pale color of yellow-poplar heartwood, its low durability, and extractives content, and the fact that yellow-poplar containers do not impart taste or odor to foodstuffs suggest the extractives may not be of interest. This is not true.

Yellow-poplar is the most toxic of all of the woods studied in this review (and in the larger report from which this review is derived); it causes severe dermatitis on contact with either the green or the wet wood, and is even more severe, after contact with the bark (Senear 1933, Woods and Calnan 1976). Fresh bark should probably not be used as a mulch or a soil conditioner because the bark appreciably retards the growth of garden pea seedlings (Allison 1965) and is toxic to seed germination according to E. G. Scott, West Virginia University, Morgantown.

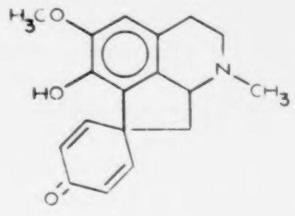
The extractives of wood, bark, cortex, leaves and seeds of yellow-poplar have been investigated (Tomita and Furukawa 1962ab; Ziyaev et al. 1975). They include alkaloids (figs. 6-25 and 6-26)—particularly aporphine alkaloids, sesquiterpenes (fig. 6-27), and lignans (fig. 6-28). No significant tannin was found in either bark or wood (Russell et al. 1942-1945).


R3
R2O
R1O
N
O
R5
R4

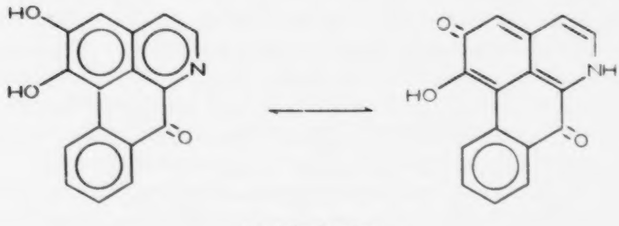
	R^1	R^2	R^3	R^4	R^5
Liriodenine	$-CH_2-$		H	H	H
***O*-methylatheroline**	CH_3	CH_3	H	OCH_3	OCH_3
Liridine	CH_3	CH_3	OCH_3	H	H
Lysicamine	CH_3	CH_3	H	H	H
Langinosine	$-CH_2-$		H	OCH_3	H


H3CO
-O
N+
CH3
O
H3CO
OCH3

Corunnine


H3CO
HO
N
CH3
O

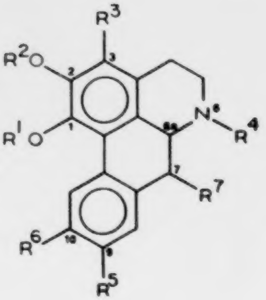
N-methylcrotsparine


HO
HO
N
O
O
HO
NH
O

Liriodendronine

M 146 176

Figure 6-25.—Some yellow-poplar alkaloids. (Drawing after Rowe and Conner 1979.)

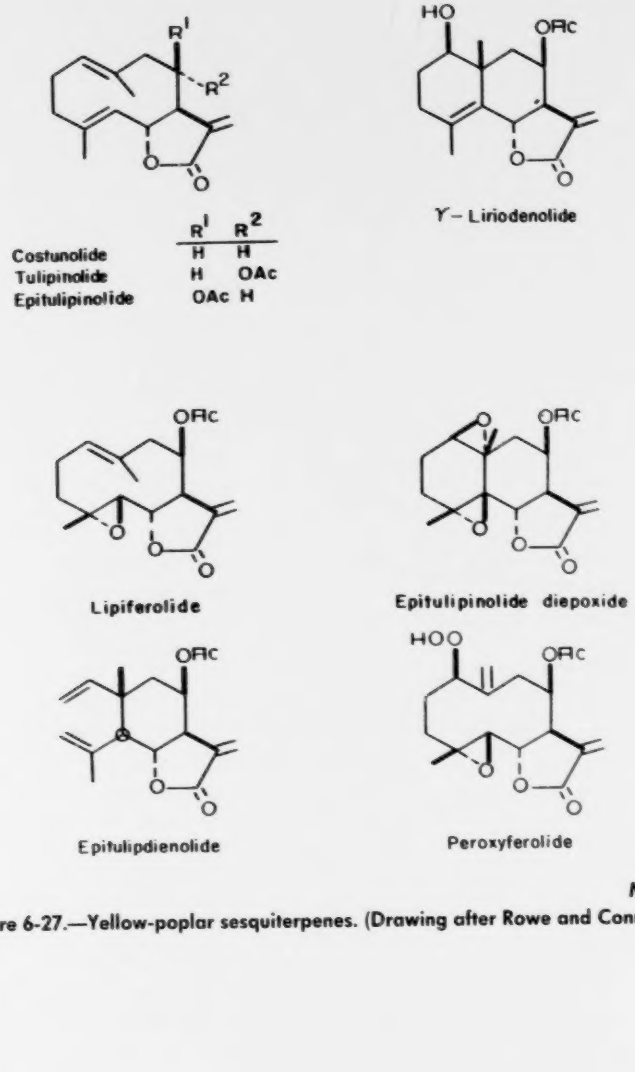


	R^1	R^2	R^3	R^4	R^5	R^6	R^7
(+)-Glaucine	CH_3	CH_3	H	CH_3	OCH_3	OCH_3	H
(+)-Norglaucine	CH_3	CH_3	H	H	OCH_3	OCH_3	H
(-)-Nuciferine	CH_3	CH_3	H	CH_3	H	H	H
(-)-Nornuciferine	CH_3	CH_3	H	H	H	H	H
(-)-*N*-acetylnornuciferine	CH_3	CH_3	H	Ac	H	H	H
(-)-Ushinsunsine	$- CH_2 -$		H	CH_3	H	H	OH
(-)-Norushinsunsine	$- CH_2 -$		H	H	H	H	OH
(-)-Asimilobine	CH_3	H	H	H	H	H	H
(-)-*N*-acetylasimilobine	CH_3	H	H	Ac	H	H	H
(+)-Thaliporphine	H	CH_3	H	CH_3	OCH_3	OCH_3	H
(+)-Predicentrine	CH_3	H	H	CH_3	OCH_3	OCH_3	H
(+)-Lirioferine	CH_3	CH_3	H	CH_3	OCH_3	OH	H
(+)-*N*-methyllaurotetanine	CH_3	CH_3	H	CH_3	OH	OCH_3	H
(+)-Liriotulipiferine	CH_3	OH	H	CH_3	OCH_3	OH	H
(+)-*N*-acetylnornantenine	CH_3	CH_3	H	Ac	$-CH_2 -$		H
(+)-3-Methoxy-*N*-acetylnornantenine	CH_3	CH_3	OCH_3	Ac	$-CH_2 -$		H
(-)-*N*-acetylanonaine	$-CH_2 -$		H	Ac	H	H	H
(-)-Tuliferoline	CH_3	CH_3	OCH_3	Ac	H	H	H
(+)-Lirinidine	H	CH_3	H	CH_3	H	H	H
(+)-Caaverine	H	CH_3	H	H	H	H	H
(+)-Isolaureline	$- CH_2 -$		H	CH_3	OCH_3	H	H
(+)-Isoroemerine	$- CH_2 -$		H	CH_3	H	H	H
(-)-Liridinine[1/]	CH_3	H	OCH_3	CH_3	H	H	H
(-)-Lirinine[1/]	H	CH_3	OCH_3	CH_3	H	H	H
(-)-Lirinine *O*-methyl ether	CH_3	CH_3	OCH_3	CH_3	H	H	H
(-)-Norlirinine *O*-methyl ether	CH_3	CH_3	OCH_3	H	H	H	H

[1/] Structure for these compounds are interchangeable.

M 146 177

Figure 6-26.—Additional yellow-poplar alkaloids. (Drawing after Rowe and Conner 1979.)



	R^1	R^2
Costunolide	H	H
Tulipinolide	H	OAc
Epitulipinolide	OAc	H

γ-Liriodenolide

Lipiferolide

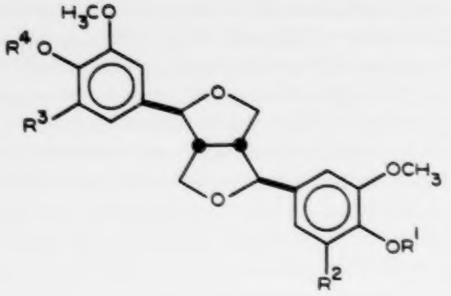
Epitulipinolide diepoxide

Epitulipdienolide

Peroxyferolide

M 146 178

Figure 6-27.—Yellow-poplar sesquiterpenes. (Drawing after Rowe and Conner 1979.)

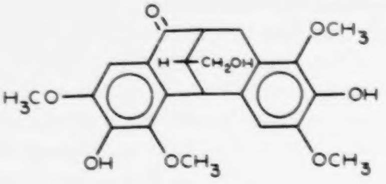


(+)-Syringaresinol ($R^1 = R^4 = H$, $R^2 = R^3 = OCH_3$)

(+)-Syringaresinol dimethyl ether ($R^1 = R^4 = CH_3$, $R^2 = R^3 = OCH_3$)

Liriodendrin ($R^1 = R^4 = \beta$-D-glucose, $R^2 = R^3 = OCH_3$)

(+)-Medioresinol ($R^1 = R^3 = R^4 = H$, $R^2 = OCH_3$)



Lirionol

M 146 179

Figure 6-28.—Yellow-poplar lignans. (Drawing after Rowe and Conner 1979.)

Presence of alkaloids in the bark probably explains why bark extracts were used medicinally for treating malaria during the War of Independence. The alkaloid glaucine is used as an antitussive in the Soviet Union. Recent investigations have shown that the heartwood alkaloid fraction has antimicrobial activity (Hufford et al. 1975).

An extensive investigation of the alkaloids in yellow-poplar wood was conducted by Chen and others (Chen and Chang 1978; Chen et al. 1976ab; Senter and Chen 1977), who studied sapwood, discolored sapwood formed after injury, heartwood, and discolored heartwood infested by micro-organisms. Glaucine, the only alkaloid detected in sapwood was the major alkaloid in the heartwood and the discolored sapwood. Other alkaloids in the heartwood and the discolored sapwood included dehydroglaucine, norglaucine, liriodenine [identical with spermatheridine, oxoushinsunsine, and micheline B (Taylor 1961)], *O*-methylatheroline (oxoglaucine), nuciferine, nornuciferene, *N*-acetylnornuciferine, norushinsunsine, asimilobine, and *N*-acetylasimilobine. At least two unidentified 1-benzyltetrahydroisoquinoline type alkaloids were found in the heartwood. Except for the oxoaporphine pigments liriodendronine and corunnine, the compounds isolated from the discolored heartwood were similar to those found in the normal heartwood. In contrast the discolored sapwood contained not only liriodendronine, corunnine, and the compounds mentioned, but in addition, thaliporphine, predicentrine, *N*-methyllaurotetanine, lirioferine, and liriotulipiferine that were not detected in either normal heartwood or discolored heartwood infested by micro-organisms. Thus the formation of these phenolic aporphines in the discolored sapwood probably did not result from microbial metabolism of glaucine, although the microbial *N*- and *O*-dealkylation of glaucine has been reported (Davis et al. 1977).

Production of aporphine alkaloids is stimulated by injury—apparently to inhibit the growth of invading micro-organisms. Thus glaucine, *N*-methyllaurotetanine, lirioferine, and liriotulipiferine have been found to have antimicrobial activity against fungi but not bacteria inhabiting the wood of yellow-poplar (Huang Hsu 1976). In addition, dehydroglaucine and liriodenine, a known cytotoxin (Warthen et al. 1969), have been identified as antimicrobial agents (Chen et al. 1974; Hufford et al. 1975).

Liriodenine and *O*-methylatheroline, which can be formed by auto-oxidation of glaucine, are responsible for the yellowish-green color of normal heartwood of yellow-poplar (Buchanan and Dickey 1960; Chen et al. 1976a; Cohen et al. 1961). Liriodendronine and corunnine are responsible in part for the discoloration of injured wood (Chen et al. 1976b; Senter and Chen 1977), which ranges from yellow-green to pink, red, purple, blue, brown, and even black. In addition, other investigations showed the presence of *N*-acetylnornantenine, 3-methoxy-*N*-acetylnornantenine (Hufford and Funderburk 1974), unshinsunsine (michelabine) (Hufford et al. 1975), *N*-acetylanonaine, and tuliferoline (Hufford 1976).

Extensive Russian investigations recently have been conducted on the alkaloids in yellow-poplar leaves with limited work on the wood and the bark. The compounds that were isolated included liridine, caaverine, lirinidine (*N*-methylcaaverine), lirinine, lirinine *O*-methyl ether, lirinine *N*-oxide, isolaureline, lysicamine, isoroemerine, nornuciferine, langinosine, liridinine, and *N*-methylcrotsparine (Abdusamatov et al. 1974, 1975; Ziyaev et al. 1973abc, 1974ab, 1975).

Lirinine and lirinine *O*-methyl ether were identified as 1-hydroxy-2, 9-dimethoxyaporphine and 1,2,9-trimethoxyaporphine, respectively, by Yunusov and others on the basis of spectroscopic analysis (Ziyaev et al. 1973c). However, the nuclear magnetic resonance (NMR) spectrum of lirinine is incompatible with the proposed structure (Chen and Chang 1978). Of the two methoxyl resonances, the one at higher field (τ 6.37) corresponded to a C-1 methoxyl resonance (Bick et al. 1961). The aromatic region of the spectrum integrated for four hydrogens constituted an ABCX spin-system corresponding to four adjacent aromatic hydrogens. An H-3 resonance around τ 3.50 was absent. In addition, the spectrum was almost identical to that of liridinine (Abdusamatov et al. 1975). Therefore, lirinine and liridinine should be isomers, i.e., 3-hydroxy-1,2-dimethoxyaporphine and 2-hydroxy-1,3-dimethoxyaporphine, respectively, or vice versa. Lirinine *O*-methyl ether should then be 1,2,3-trimethoxyaporphine. Although the structure 2-hydroxy-1,3-dimethoxyaporphine. was assigned to liridinine by the Russian authors on the basis of the NMR spectrum, C.-L. Chen, North Carolina University, Raleigh, believes that further research is required to establish the structures of lirinine and liridinine.

The isolation of the proaporphine alkaloid *N*-methylcrotsparine and the benzyltetrahydroisoquinoline alkaloids mentioned are interesting because compounds of this type are postulated as intermediates in the biosynthesis of aporphine alkaloids from phenylalanine and tyrosine (Barton et al. 1967; Gottlieb 1972).

Yellow-poplar stembark extractives contain a series of sesquiterpene lactones: Costunolide, tulipinolide, epitulipinolide, epitulipdienolide, and γ-liriodenolide (Doskotch and El-Feraly 1969, 1970; Doskotch et al. 1972ab, 1975). The related compounds lipiferolide, epitulipinolide diepoxide, and peroxyferolide (the first naturally occurring germacranolide hydroperoxide) have been observed in the leaves (Doskotch et al. 1976, 1977). Most of these compounds are cytotoxic and inhibit feeding by gypsy moth larvae (*Porthetria dispar* L.) (Doskotch et al. 1975). Interestingly, Doskotch finds that the antifeeding activity is greater for mixtures of these compounds than for the individual compounds.

In addition to the noraporphine alkaloids and sesquiterpene lactones, yellow-poplar bark extracts also contain large amounts of simple sugars, some phenolics and coloring materials, a pleasant smelling essential oil, esculetin dimethyl ether (fig. 6-15) (Tomita and Furukawa 1962b), liriodentritol (mesoinositol-1,4-dimethyl ether) and methyl syringate (Chen and Chang 1978). The amount of total alkaloids in the extract is insignificant although trace amounts of norlirinine *O*-methyl ether, nornuciferine, and *N*-(2-hydroxy-2-phenylethyl) benzamide were isolated from this fraction (Chen and Chang 1978). The lignans (+)-pinoresinol (fig. 6-12), (+)-syringaresinol, the coniferyl-sinapyl analog (+)-medioresinol, and their monoglucosides and diglucosides, e.g., liriodendrin, as well as the unusual lignan lirionol were also found in the bark (Chen and Chang 1978; Dickey 1958; Fujimoto and Higuchi 1977a).

Liriodendrin is a derivative of (+)-syringaresinol (lirioresinol B) (Briggs et al. 1968, Maslen et al. 1962). Dickey's "lirioresinol C" was shown to be impure lirioresinol B (Briggs et al. 1968). (+)-Syringaresinol, syringaresinol dimethyl ether, and the simple phenol, syringaldehyde, were found in yellow-poplar heartwood (Chen et al. 1967ab; Hufford et al. 1975). In studies on the biogenesis of the lignans in the bark (Fujimoto and Higuchi 1977b), sinapyl alcohol was found, as expected, the best precursor. However, the free syringaresinol and the liriodendrin were, surprisingly, the (−) form in contrast to the (+)-isomers normally found. Apparently a tree can synthesize both antipodes. In addition to free syringaresinol and its monoglucoside, also found were the coniferyl analog, (+)-pinoresinol, and (+)-medioresinol.

Yellow-poplar contains a most unusual series of extractives including compounds of unusual structures as well as an extraordinary array of alkaloids, a class of extractives seldom found in temperate zone trees. The largest group of these are the aporphine alkaloids. They occur in two series depending on the stereochemistry at 6a. The compounds with a hydrogen at this position extending above the plane of the ring (*S*-absolute stereochemistry) are generally dextrorotatory [(+)]. Those with a hydrogen extending below the plane of the ring (*R*-absolute stereochemistry) are generally levorotatory [(−)].

6-7 INORGANIC COMPONENTS

Inorganic components in wood comprise those non-constituent elements, largely metallic or alkaline earth that are present as a natural result of growth. These elements are normally brought into the tree from the soil through the root system and sap stream; perhaps some also come from precipitation and airborne particles. As elements of the biogenesis of wood formation, mineral components apparently play an important role in determining cell wall thickness, cell length, cell type distribution, sap transport, enzyme activity, and in the deposition of crystals and perhaps extractives. Precise pathways and modes of uptake, distribution, and deposition are largely unknown. Quantities rarely exceed 1-percent of dry weight of stemwood.

Since specific elements are essential for plant growth, greatest scientific attention has been devoted to the occurrence of these inorganic nutrients in the soil, and to their cycling from soil to plant and return to soil through decay. Much research has been concerned with soil deficiencies and their correction through fertilization and special treatments. Analysis of entire seedlings or small trees to indicate nutritional status is common practice.

Readers interested in aspects of nutrient drain caused by intensive harvest of above- and below-ground tree portions from southern woodlands should read, "Principles of maintaining productivity on prepared sites", symposium proceedings (Tippin 1978), this compendium contains views of numerous scientists working with southern tree species.

Altman and Dittmer (1964) have proposed classification of inorganic elements in trees as follows:

Constituent C, O, H, N, P, S, Cl
Essential:
  Major—Ca, K, Mg, Na, Si
  Minor—B, Mn, Fe, Mo, Cu, Zn
Commonly found: Ag, Al, Ba, Co, Cr, Ni, Pb, Rb, Sr, Ti

A wide variety of other elements has been reported; presumably their presence depends on site and geographic location as well as other factors. Notable by its low content is sulfur (0.00 to 0.15 percent); therefore, when wood or bark is burned, sulfurous compounds are only minutely present in the combustion gases or in the ash (National Council of the Paper Industry for Air and Steam Improvement, Inc. 1978)—a distinct advantage over fossil fuels. Nitrogenous products may be present in wood combustion gases, however.

Because of their potential use as fuel, interest in inorganic components of pine-site hardwoods centers on their ash content. Some chemical utilization processes, however, are significantly affected by presence of mineral elements in minute amounts; users of such processes therefore need data on mineral content.

In some cases, mineral content of tree rings has provided clues to past events. Thus, lead content in wood grown near roads was significantly greater during the latest than in the prior decade; the increase was attributed to automobile exhaust fumes (Rolfe 1974).

METHODS OF ANALYSIS OF INORGANIC CONTENT

Limited knowledge of the factors affecting the variation in inorganic content of wood makes it difficult to adequately sample tree populations to determine these elements. Because these elements are present in wood only at very low levels—usually measured in parts per million (p.p.m.) of dry matter—great care in sampling and highly precise laboratory methods are essential.

Nondestructive analysis.—Bowen and Gibbens (1963) described a technique (activation analysis) that does not require prior ashing to make determination for manganese, copper, potassium, sodium, calcium, magnesium, vanadium, cobalt, zinc, and molybdenum content. Procedures and detection limits were given by Young and Guinn (1966). Wardell and Hart (1973) used an electron microprobe X-ray analyzer-scanning microscope to study mineral contents in selected cellular tissue; elements evaluated were magnesium, potassium, calcium, phosphorus, chlorine, sulfur, and manganese.

Destructive analysis.—Hergert et al.[1], in their experiments with southern hardwoods, obtained accurate and consistent results (table 6-1) with minimum loss of volatile metallic compounds. Their ashing procedure called for ignition of a 40-mesh wood sample (about a gram) in a platinum dish at 575°C. In some instances reignition was necessary when inspection of the ash residue indicated presence of carbon particles.

Manwiller[6], in his analysis of inorganic content of 6-inch pine-site hardwoods sampled Southwide, ground stemwood, branchwood, stembark, and branchbark to 40 mesh and analyzed them separately by ashing them for 4 hours in a muffle furnace at 575°C. Specimens were not treated with nitric acid prior to ashing. Two replications of ash content determination were made for each of 10 trees of each species, and the values for the two replications averaged (table 6-18).

To determine mineral content (table 6-19) ashed samples of the 22 species of stemwood, branchwood, stembark, and branchbark were dissolved in 0.3 N nitric acid, and evaluated by testing on a Perkin-Elmer Model 360 Atomic Absorption Spectrophotometer. Elements considered were iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), sodium (Na), magnesium (Mg), calcium (Ca), potassium (K), and aluminum (Al). Phosphorus (P) content was determined on a Perkin-Elmer UV-VIS Spectrophotometer by the ascorbic acid method (John 1970).

Stock solutions were made for each element in accordance with instructions outlined by Perkin-Elmer. Aliquots of the stock solutions were combined and diluted with deionized water to form the standards by which the instrument was calibrated. Determination of sodium, magnesium, calcium, potassium, and manganese required addition of a strontium ion (1,500 ppm solution of $SrCl_2$ in 0.3N HNO_3) in both samples and standards to mask the effect of various interferences. Therefore, two separate sets of standards were made: one with the strontium ion and one without. Likewise, two blank standards of 0.3N HNO_3 were made for zeroing the instrument: one with and the other without the strontium addition.

Zinc, copper, and iron did not require the addition of strontium, and could be tested without dilution except in cases where high concentrations of an element required dilution in order to bring it within the range of the standards.

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[6] Unpublished data in Final Report FS-SO-3201-1.41, dated March 19, 1981. U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Pineville, La.

AMONG-SPECIES VARIATION

Data on ash content of wood and bark from 6-inch-diameter, pine-site hardwoods of 22 species sampled throughout their southern ranges (table 6-18) indicated averages and among-species ranges as follows (percentage of unextracted ovendry weight):

Tissue	Average	Minimum	Maximum
	Percent		
Wood			
Stemwood	0.75	0.43 (northern red oak and yellow-poplar)	1.33 (hackberry)
Branchwood	.94	.60 (sweetbay)	1.45 (hackberry)
Bark			
Stembark	7.87	4.08 (yellow-poplar)	12.12 (winged elm)
Branchbark	6.76	4.12 (yellow-poplar)	11.75 (winged elm)

Thus, variation among the species is significant. Even among the 11 oak species, ash content in all components varied significantly with species. For example, the stembark of white oak and post oak have about 11 percent ash content, while that of scarlet oak has less than half this amount (5.18 percent).

See tables 14-9 and 14-10 for ash and mineral content of wood and bark in stump-root systems.

TABLE 6-18.—*Ash content in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] (Data from Manwiller[3])

Species	Stemwood[4]	Stembark[4]	Branchwood[5]	Branchbark[5]
	Percent			
Ash, green	.68	7.31	1.00	5.44
	(.18)	(1.26)	(.42)	(1.08)
Ash, White	.66	6.52	1.01	4.78
	(.05)	(1.47)	(.33)	(1.20)
Elm, American	.94	10.29	.96	10.26
	(.18)	(1.26)	(.14)	(1.99)
Elm, winged	.86	12.12	.90	11.75
	(.19)	(2.24)	(.16)	(1.91)
Hackberry[7]	1.33	11.50	1.45	11.37
	(.18)	(1.93)	(.30)	(1.84)
Hickory, sp.	1.02	8.55	1.12	8.08
	(.20)	(2.86)	(.28)	(2.90)
Maple, red	.50	4.78	.65	5.00
	(.12)	(1.08)	(.13)	(1.22)
Oak, black	.74	8.77	1.17	7.47
	(.30)	(1.39)	(.27)	(1.97)
Oak, blackjack	1.12	6.96	1.03	5.40
	(.22)	(1.14)	(.23)	(1.62)
Oak, cherrybark	.75	8.80	1.04	7.35
	(.14)	(1.43)	(.23)	(1.49)
Oak, laurel	.88	6.48	.92	5.58
	(.13)	(1.22)	(.16)	(1.76)
Oak, northern red	.43	6.75	.93	6.16
	(.13)	(1.06)	(.27)	(1.53)
Oak, post	.94	11.48	1.22	8.01
	(.35)	(2.67)	(.42)	(2.69)
Oak, scarlet	.46	5.18	.74	4.66
	(.12)	(1.30)	(.20)	(1.58)
Oak, Shumard	.55	6.71	.82	5.57
	(.18)	(2.08)	(.19)	(1.83)
Oak, southern red	.88	7.64	1.21	6.01
	(.30)	(1.41)	(.34)	(1.40)
Oak, water	.90	6.58	.97	5.66
	(.24)	(1.87)	(.34)	(1.44)
Oak, white	.68	10.59	1.07	6.81
	(.33)	(2.96)	(.57)	(2.27)
Sweetbay	.50	5.70	.60	5.92
	(.05)	(1.72)	(.12)	(1.10)

See footnotes on page 436.

TABLE 6-18.—*Ash content in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] (Data from Manwiller[3])—Continued

Species	Stemwood[4]	Stembark[4]	Branchwood[5]	Branchbark[5]
	Percent[6]			
Sweetgum	.53	7.95	.63	7.68
	(.10)	(1.18)	(.08)	(1.82)
Tupelo, black	.66	8.32	.67	5.61
	(.17)	(1.76)	(.14)	(1.48)
Yellow-poplar	.43	4.08	.63	4.12
	(.10)	(1.05)	(.32)	(.96)

[1] Values determined on 40-mesh wood or bark ashed at 575°C for 5 hours.

[2] The first value tabulated under each heading is the average value for 10 trees; below (in parenthesis) is the within-species standard deviation.

[3] Manwiller, F. G. Unpublished data in Final Report FS-SO-3201-1.41, dated March 19, 1981. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Pineville, La.

[4] From a point 6 inches above ground level to the point where the central stem could no longer be distinguished or to a 0.5-inch minimum diameter outside bark.

[5] From the point of juncture with central stem extending out to a branch diameter of 0.5 inches outside bark.

[6] Percentage of unextracted ovendry weight; see tables 3-1 and 16-3 for description of trees sampled.

[7] Mostly sugarberry.

The mineral analyses shown in table 6-19 indicate that among-species variations are significant, as follows (stemwood and stembark data only are summarized, but those for branchwood and branchbark show comparable among-species variation):

Mineral and tissue	Minimum		Maximum	
	Parts/million of ovendry weight			
Fe				
Stemwood	35	yellow-poplar	97	southern red oak
Stembark	76	white oak	412	hackberry
Zn				
Stemwood	2	blackjack oak	62	white oak
Stembark	10	blackjack oak	157	white oak
Cu				
Stemwood	0	winged elm	24	green ash
Stembark	3	scarlet oak	73	green ash
Mn				
Stemwood	2	white ash	220	hickory
Stembark	96	black oak	1,302	hickory
Na				
Stemwood	51	Shumard oak	348	southern red oak
Stembark	148	Shumard oak	2,762	laurel oak
Mg				
Stemwood	139	northern red oak	1,138	hickory
Stembark	491	blackjack oak	2,247	white ash
Ca				
Stemwood	908	northern red oak	4,006	hackberry
Stembark	6,933	sweetbay	52,420	post oak

Mineral and tissue	Minimum	Maximum
	Parts/million of ovendry weight	
K		
Stemwood	517 yellow-poplar	3,963 hackberry
Stembark	376 scarlet oak	4,874 American elm
Al		
Stemwood	5 white ash	164 post oak
Stembark	67 red maple	604 hackberry
P		
Stemwood	71 scarlet oak	560 winged elm
Stembark	165 blackjack oak	610 American elm

Hergert et al.[1] found that in the 18 species (29 combinations of species and location) listed in table 6-1, the following exceeded 0.5 percent ash:

Species	Location	Stemwood ash content
		--Percent--
Elm, American	Georgia	0.8
Hickory sp.	Georgia	1.1
Hickory, pignut	Tennessee	.6
Oak, blackjack	Tennessee	1.3
Oak, white	Georgia	1.0
Tupelo, black	Tennessee	.6

Of the species listed in table 6-2, only eastern cottonwood and live oak stemwood from Georgia averaged over 0.5 percent ash content; both averaged 0.6 percent.

TABLE 6-19.—*Content of 10 minerals in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] (Data from Manwiller[3])

Species and tree portation	Fe	Zn	Cu	Mn	Na	Mg	Ca	K	Al	P
	Parts/million									
Ash, green										
Stemwood[4]	70	4	24	23	238	467	1,992	1,560	25	237
	(56)	(4)	(12)	(15)	(197)	(147)	(780)	(438)	(20)	(84)
Stembark[4]	166	42	73	140	451	2,062	27,792	2,452	269	302
	(90)	(12)	(36)	(29)	(256)	(795)	(5,922)	(1,637)	(132)	(100)
Branchwood[5]	61	4	37	27	210	624	2,458	1,703	25	519
	(51)	(6)	(28)	(16)	(184)	(176)	(1,141)	(550)	(20)	(296)
Branchbark[5]	112	43	66	137	360	1,727	21,115	2,736	154	585
	(55)	(20)	(61)	(34)	(199)	(394)	(4,934)	(1,156)	(53)	(299)
Ash, white										
Stemwood[4]	70	7	18	2	270	376	1,500	1,550	5	212
	(35)	(5)	(10)	(2)	(210)	(71)	(292)	(317)	(9)	(53)
Stembark[4]	138	24	52	116	551	2,247	27,357	3,585	128	346
	(71)	(6)	(36)	(49)	(349)	(945)	(9,562)	(1,885)	(117)	(50)
Branchwood[5]	80	9	30	8	288	629	2,955	1,891	7	412
	(36)	(5)	(17)	(5)	(200)	(136)	(1,665)	(264)	(8)	(143)
Branchbark[5]	113	28	38	111	436	1,499	20,611	3,131	52	433
	(40)	(11)	(40)	(46)	(243)	(476)	(6,853)	(498)	(42)	(66)
Elm, American										
Stemwood[4]	76	4	1	10	320	640	2,408	2,313	19	340
	(26)	(4)	(1)	(8)	(244)	(233)	(536)	(1,115)	(20)	(157)
Stembark[4]	177	30	7	221	514	1,116	35,225	4,874	141	610
	(59)	(12)	(2)	(100)	(237)	(467)	(5,674)	(1,260)	(92)	(190)
Branchwood[5]	79	5	1	12	253	690	2,402	2,806	15	385
	(25)	(5)	(1)	(9)	(187)	(315)	(503)	(1,309)	(17)	(156)
Branchbark[5]	176	42	8	245	519	1,298	33,018	5,456	160	863
	(63)	(16)	(2)	(68)	(205)	(517)	(7,813)	(1,131)	(62)	(211)

See footnotes at the end of table.

TABLE 6-19.—*Content of 10 minerals in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] (Data from Manwiller[3])—Continued

Species and tree portation	Fe	Zn	Cu	Mn	Na	Mg	Ca	K	Al	P
	Parts/million									
Elm, winged										
Stemwood[4]	63	8	0	82	177	509	1,975	1,819	12	560
	(22)	(7)	(-)	(40)	(198)	(194)	(633)	(399)	(18)	(368)
Stembark[4]	155	26	8	395	306	898	45,524	4,375	121	506
	(53)	(8)	(3)	(207)	(247)	(192)	(7,612)	(1,209)	(40)	(100)
Branchwood[5]	74	9	0	94	170	649	1,808	1,948	15	656
	(33)	(7)	(-)	(48)	(194)	(246)	(521)	(366)	(19)	(355)
Branchbark[5]	190	35	6	437	333	1,025	46,148	4,136	170	736
	(54)	(7)	(3)	(240)	(253)	(192)	(9,579)	(795)	(64)	(214)
Hackberry[6]										
Stemwood[4]	63	6	2	17	68	614	4,006	3,963	20	391
	(30)	(5)	(2)	(7)	(47)	(130)	(718)	(3,871)	(14)	(161)
Stembark[4]	412	19	20	104	204	1,162	48,344	3,518	604	602
	(289)	(10)	(7)	(77)	(85)	(351)	(6,940)	(702)	(561)	(133)
Branchwood[5]	57	8	2	22	56	930	4,171	3,647	19	526
	(18)	(7)	(1)	(8)	(28)	(383)	(1,164)	(903)	(15)	(172)
Branchbark[5]	152	19	20	75	176	1,450	50,975	4,020	118	682
	(31)	(9)	(7)	(45)	(87)	(276)	(8,074)	(1,162)	(61)	(236)
Hickory, sp.										
Stemwood[4]	44	44	4	220	155	1,138	2,477	1,492	94	242
	(23)	(23)	(6)	(106)	(165)	(371)	(594)	(495)	(55)	(66)
Stembark[4]	99	141	6	1,302	320	1,966	37,461	1,981	254	337
	(37)	(72)	(2)	(582)	(245)	(534)	(14,981)	(588)	(74)	(70)
Branchwood[5]	44	32	2	227	158	963	3,133	1,548	110	337
	(21)	(16)	(1)	(133)	(171)	(398)	(1,142)	(346)	(70)	(123)
Branchbark[5]	112	146	5	1,132	335	2,096	34,456	2,530	243	423
	(37)	(75)	(1)	(530)	(205)	(559)	(12,927)	(668)	(74)	(122)

See footnotes at the end of table.

TABLE 6-19.—*Content of 10 minerals in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] (Data from Manwiller[3])—Continued

Species and tree portation	Fe	Zn	Cu	Mn	Na	Mg	Ca	K	Al	P
	Parts/million									
Maple, red										
Stemwood[4]	75	8	4	82	198	290	1,937	974	22	120
	(48)	(5)	(1)	(46)	(228)	(63)	(375)	(309)	(27)	(27)
Stembark[4]	78	41	8	543	329	733	24,257	2,939	67	510
	(67)	(12)	(4)	(283)	(206)	(166)	(6,027)	(676)	(24)	(126)
Branchwood[5]	67	8	4	120	188	330	2,286	1,275	15	198
	(32)	(6)	(1)	(75)	(229)	(58)	(530)	(188)	(22)	(54)
Branchbark[5]	89	43	11	574	309	913	22,880	3,615	89	658
	(34)	(11)	(4)	(316)	(188)	(86)	(4,884)	(468)	(29)	(147)
Oak, black										
Stemwood[4]	76	6	6	90	144	323	2,065	1,389	50	110
	(36)	(4)	(2)	(51)	(138)	(387)	(1,033)	(603)	(31)	(35)
Stembark[4]	120	17	7	96	218	599	38,653	1,313	136	250
	(100)	(12)	(2)	(56)	(141)	(238)	(10,847)	(206)	(83)	(28)
Branchwood[5]	63.	6	7	175	157	482	3,153	1,945	51	326
	(29)	(3)	(2)	(83)	(146)	(210)	(993)	(409)	(34)	(143)
Branchbark[5]	124	21	7	178	196	725	33,232	1,853	100	424
	(93)	(9)	(1)	(92)	(151)	(276)	(9,742)	(337)	(49)	(85)
Oak, blackjack										
Stemwood[4]	73	2	2	96	84	408	2,230	3,255	36	138
	(41)	(3)	(2)	(52)	(119)	(235)	(779)	(730)	(21)	(35)
Stembark[4]	214	10	5	600	212	491	26,811	983	252	165
	(189)	(11)	(1)	(241)	(242)	(188)	(3,779)	(340)	(149)	(27)
Branchwood[5]	90	4	13	139	79	425	2,540	1,832	34	200
	(56)	(12)	(43)	(70)	(105)	(164)	(993)	(568)	(23)	(33)
Branchbark[5]	140	15	6	594	188	613	21,980	1,455	166	294
	(67)	(14)	(3)	(197)	(193)	(191)	(6,636)	(694)	(65)	(84)

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end of table

TABLE 6-19.—*Content of 10 minerals in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] (Data from Manwiller[3])—Continued

Species and tree portation	Fe	Zn	Cu	Mn	Na	Mg	Ca	K	Al	P
	Parts/million									
Oak, cherrybark										
Stemwood[4]	66	6	4	196	223	315	1,830	1,508	109	160
	(32)	(4)	(1)	(52)	(181)	(92)	(545)	(262)	(48)	(42)
Stembark[4]	109	12	6	988	314	618	38,169	785	114	208
	(23)	(6)	(2)	(474)	(227)	(155)	(7,031)	(319)	(50)	(40)
Branchwood[5]	75	5	4	125	223	493	2,677	1,709	123	394
	(23)	(5)	(2)	(38)	(191)	(208)	(908)	(346)	(44)	(184)
Branchbark[5]	117	17	6	891	287	1,051	30,067	1,877	139	416
	(38)	(9)	(2)	(354)	(195)	(364)	(7,594)	(701)	(71)	(110)
Oak, laurel										
Stemwood[4]	66	5	4	87	212	678	2,249	1,402	25	226
	(31)	(5)	(2)	(63)	(185)	(264)	(428)	(440)	(23)	(113)
Stembark[4]	164	20	9	562	2,762	729	27,436	1,005	194	238
	(121)	(11)	(2)	(274)	(2,757)	(229)	(5,501)	(460)	(328)	(52)
Branchwood[5]	74	6	4	108	190	1,160	2,306	1,347	28	467
	(35)	(4)	(1)	(77)	(163)	(1,393)	(452)	(527)	(24)	(196)
Branchbark[5]	137	33	11	628	2,758	1,232	22,802	1,573	93	455
	(36)	(18)	(2)	(322)	(2,428)	(254)	(7,367)	(674)	(49)	(98)
Oak, northern red										
Stemwood[4]	77	5	6	183	149	139	908	998	34	80
	(28)	(8)	(2)	(28)	(167)	(85)	(409)	(246)	(31)	(56)
Stembark[4]	120	10	6	664	224	616	27,326	1,688	131	221
	(59)	(5)	(5)	(358)	(174)	(193)	(3,960)	(2,190)	(62)	(34)
Branchwood[5]	79	8	6	290	191	655	2,073	1,799	29	336
	(35)	(8)	(2)	(90)	(174)	(371)	(839)	(370)	(29)	(235)
Branchbark[5]	88	17	5	680	215	1,120	25,062	1,418	98	371
	(38)	(9)	(1)	(361)	(180)	(362)	(5,954)	(586)	(47)	(89)

See footnotes at the end of table.

TABLE 6-19.—*Content of 10 minerals in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] (Data from Manwiller[3])—Continued

Species and tree portion	Fe	Zn	Cu	Mn	Na	Mg	Ca	K	Al	P
	Parts/million									
Oak, post										
Stemwood[4]	73	8	5	72	213	396	2,499	1,550	164	123
	(45)	(5)	(7)	(49)	(195)	(165)	(1,335)	(306)	(90)	(34)
Stembark[4]	100	13	7	686	462	1,501	52,420	1,204	131	243
	(122)	(6)	(2)	(354)	(306)	(447)	(15,350)	(481)	(121)	(51)
Branchwood[5]	59	11	3	128	232	564	4,101	1,485	188	252
	(27)	(6)	(2)	(85)	(176)	(206)	(4,138)	(342)	(94)	(65)
Branchbark[5]	243	19	9	983	472	1,813	30,412	2,026	308	405
	(381)	(8)	(2)	(643)	(324)	(612)	(15,239)	(353)	(288)	(76)
Oak, scarlet										
Stemwood[4]	78	7	3	110	164	169	929	1,168	35	71
	(26)	(7)	(7)	(54)	(174)	(47)	(327)	(247)	(18)	(35)
Stembark[4]	107	20	3	805	228	588	24,889	376	110	227
	(54)	(10)	(2)	(479)	(171)	(150)	(5,433)	(279)	(65)	(38)
Branchwood[5]	65	9	3	204	191	372	1,522	1,686	31	235
	(26)	(6)	(4)	(110)	(184)	(79)	(654)	(316)	(22)	(85)
Branchbark[5]	76	27	2	1,080	232	1,029	22,345	1,021	96	400
	(31)	(11)	(1)	(586)	(160)	(234)	(7,055)	(561)	(59)	(63)
Oak, Shumard										
Stemwood[4]	46	4	2	60	51	215	1,689	1,222	55	88
	(29)	(2)	(2)	(60)	(70)	(80)	(774)	(397)	(27)	(35)
Stembark[4]	129	13	11	608	148	585	30,858	824	141	259
	(74)	(9)	(2)	(503)	(109)	(213)	(10,815)	(482)	(62)	(54)
Branchwood[5]	43	7	2	114	68	436	2,345	1,656	63	286
	(26)	(6)	(2)	(112)	(98)	(106)	(958)	(481)	(44)	(103)
Branchbark[5]	94	16	11	609	140	817	24,360	1,530	118	442
	(35)	(11)	(2)	(491)	(106)	(210)	(9,014)	(409)	(29)	(82)

See footnotes at the end of table.

TABLE 6-19.—*Content of 10 minerals in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] (Data from Manwiller[3])—Continued

Species and tree portation	Fe	Zn	Cu	Mn	Na	Mg	Ca	K	Al	P
	Parts/million									
Oak, southern red										
Stemwood[4]	97	7	6	105	348	406	2,169	1,660	82	153
	(44)	(4)	(2)	(33)	(216)	(225)	(1,369)	(345)	(26)	(156)
Stembark[4]	134	14	4	707	406	608	31,399	1,080	128	180
	(64)	(6)	(1)	(295)	(262)	(168)	(7,556)	(266)	(57)	(51)
Branchwood[5]	79	8	7	189	308	561	3,436	1,855	81	309
	(41)	(5)	(2)	(76)	(230)	(189)	(1,545)	(408)	(34)	(167)
Branchbark[5]	99	16	4	576	356	634	23,123	1,488	104	350
	(30)	(9)	(2)	(242)	(239)	(199)	(6,993)	(550)	(49)	(100)
Oak, water										
Stemwood[4]	61	9	5	118	244	358	2,160	1,842	71	238
	(28)	(5)	(1)	(65)	(188)	(107)	(793)	(564)	(19)	(304)
Stembark[4]	113	34	8	658	331	653	32,419	942	91	280
	(56)	(14)	(1)	(386)	(207)	(225)	(7,736)	(616)	(31)	(109)
Branchwood[5]	46	10	5	175	266	549	2,344	1,894	71	344
	(23)	(6)	(2)	(112)	(208)	(236)	(1,303)	(784)	(30)	(223)
Branchbark[5]	83	42	8	601	356	913	27,116	1,343	93	415
	(24)	(10)	(1)	(323)	(228)	(259)	(6,539)	(658)	(35)	(84)
Oak, white										
Stemwood[4]	70	62	2	59	216	294	1,976	1,128	32	75
	(39)	(54)	(2)	(26)	(234)	(314)	(1,320)	(398)	(23)	(25)
Stembark[4]	76	157	16	678	374	686	20,150	674	70	248
	(29)	(85)	(6)	(290)	(204)	(356)	(14,047)	(517)	(35)	(54)
Branchwood[5]	69	79	2	114	253	377	3,616	1,393	33	240
	(45)	(55)	(2)	(58)	(192)	(138)	(2,704)	(259)	(16)	(67)
Branchbark[5]	86	195	17	714	400	1,009	29,982	1,424	100	407
	(27)	(59)	(6)	(346)	(221)	(549)	(14,276)	(482)	(50)	(72)

See footnotes at the end of table.

TABLE 6-19.—*Content of 10 minerals in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] (Data from Manwiller[3])—Continued

Species and tree portation	Fe	Zn	Cu	Mn	Na	Mg	Ca	K	Al	P
	Parts/million									
Sweetbay										
Stemwood[4]	64	6	4	51	166	356	1,091	820	27	220
	(24)	(5)	(1)	(28)	(132)	(206)	(337)	(304)	(18)	(52)
Stembark[4]	96	16	6	341	304	992	6,933	1,670	100	589
	(41)	(6)	(2)	(188)	(216)	(379)	(1,415)	(972)	(46)	(148)
Branchwood[5]	61	7	4	65	181	407	1,300	1,165	32	281
	(25)	(5)	(2)	(39)	(158)	(144)	(316)	(317)	(17)	(34)
Branchbark[5]	110	19	7	380	260	1,180	6,656	1,738	126	601
	(33)	(22)	(1)	(187)	(207)	(453)	(1,248)	(909)	(54)	(89)
Sweetgum										
Stemwood[4]	79	7	3	97	294	391	1,240	825	48	225
	(41)	(6)	(2)	(71)	(185)	(82)	(228)	(159)	(23)	(59)
Stembark[4]	100	56	8	930	395	1,431	22,448	2,847	189	365
	(47)	(11)	(2)	(451)	(233)	(370)	(4,764)	(954)	(58)	(61)
Branchwood[5]	76	7	4	104	264	368	1,382	1,289	44	302
	(25)	(5)	(2)	(67)	(136)	(79)	(289)	(276)	(33)	(75)
Branchbark[5]	101	64	7	922	318	1,493	21,537	3,243	180	483
	(34)	(21)	(2)	(476)	(157)	(342)	(5,689)	(740)	(69)	(83)
Tupelo, black										
Stemwood[4]	57	9	4	167	227	810	1,460	1,146	59	156
	(26)	(6)	(2)	(173)	(211)	(187)	(557)	(324)	(30)	(64)
Stembark[4]	90	24	9	872	426	2,134	33,764	2,296	188	328
	(35)	(9)	(2)	(420)	(365)	(922)	(7,701)	(709)	(56)	(70)
Branchwood[5]	51	8	6	149	220	642	1,304	1,454	55	241
	(24)	(6)	(3)	(127)	(198)	(159)	(385)	(373)	(28)	(119)
Branchbark[5]	116	32	10	1,136	518	1,766	20,912	3,304	207	527
	(30)	(26)	(2)	(1,017)	(429)	(166)	(6,508)	(881)	(56)	(76)

See footnotes at the end of table.

TABLE 6-19.—*Content of 10 minerals in stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2]
(Data from Manwiller[3])—Continued

Species and tree portation	Fe	Zn	Cu	Mn	Na	Mg	Ca	K	Al	P
	Parts/million									
Yellow-poplar										
Stemwood[4]	35	8	3	48	258	265	1,182	517	14	108
	(17)	(8)	(1)	(38)	(194)	(82)	(313)	(228)	(19)	(23)
Stembark[4]	82	23	8	476	408	1,777	12,021	3,607	285	562
	(37)	(11)	(2)	(438)	(288)	(727)	(4,440)	(1,925)	(98)	(181)
Branchwood[5]	46	7	4	58	226	300	1,807	768	24	191
	(33)	(6)	(1)	(49)	(207)	(71)	(1,279)	(178)	(30)	(53)
Branchbark[5]	94	28	8	431	366	1,710	11,512	3,028	297	603
	(36)	(17)	(3)	(248)	(198)	(516)	(3,494)	(1,252)	(114)	(179)

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[1] See text for analysis procedure.
[2] Each value tabulated is the average for 10 trees. Below (in parentheses) is the within-species standard deviation. See table 3-1 for a description of the trees sampled.
[3] Manwiller, F. G. Unpublished data in Final Report FS-SO-3201-1.41, dated March 19, 1981. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Pineville, La.
[4] From a point 6 inches above ground level to the point where the central stem could no longer be distinguished or to a 0.5-inch minimum diameter outside bark.
[5] From the point of juncture with central stem extending out to a branch diameter of 0.5 inches outside bark.
[6] Mostly sugarberry.

Choong et al. (1976) sampled the sapwood of ten sweetgum, ten red oaks (*Quercus* sp.), and ten ash (*Fraxinus* sp.) trees near Plaquemine, La.; ash contents averaged 0.5, 0.9, and 0.9 percent respectively. Sapwood mineral contents averaged as follows:

Element	Sweetgum	Red oak	Ash
	-----------------	Parts/million	-----------------
Calcium	737	2,085	1,575
Magnesium	280	316	179
Manganese	17	27	—
Phosphorus	234	417	601
Potassium	1,154	2,178	2,576
Sodium	89	115	266
Zinc	124	29	24

Comparable data for inner and outer bark of these trees is tabulated in table 13-39. Ash content in the stemwood was less than one-tenth that found in the bark (8.9 to 12.8 percent).

Cutter et al. (1980) employed neutron activation analysis to determine the mineral content of white oak after charring in a flowing nitrogen atmosphere; their results follow:

Mineral	Concentration
	Parts/million
Al	6
Ca	674
Cl	8
K	780
Mg	11
Mn	2
Na	3

Thomas (1977) found that black tupelo concentrates cobalt in its tissues to a far greater degree than most other species. Dormant black tupelo tissues contained 31 to 140 times more cobalt than the average (composite) of red maple, yellow-poplar, mockernut hickory, and white oak, as follows:

Tree coponent	Black tupelo	4-species composite
	---------------- Parts/million	----------------
Stemwood	144	1.7
Stembark	53	.9
Branches	112	.8
Roots	68	2.2

WITHIN-SPECIES VARIATION

Standard deviations in ash and mineral content among 10 trees measuring 6 inches in dbh of each of 22 species of pine-site hardwoods are given in tables 6-18 and 6-19.

Young and Carpenter (1967) found that the mineral content of complete red maple trees sampled in Maine—both absolute and as a proportion of ovendry weight—varied with tree height as follows (the 10-, 20-, and 30-foot-high complete trees, including foliage, branches, stem, and roots, had average ovendry weights of 644, 4,015, and 11,888 grams):

Mineral	Tree height (feet)		
	10	20	30
	Grams/tree		
Al	0.035	0.201	0.558
Mn	.166	.948	2.711
Mo	.002	.015	.042
Ca	3.596	22.062	64.732
P	.507	2.799	7.782
Mg	.377	2.103	5.909
Zn	.019	.119	.352
Cu	.002	.015	.040
Fe	.063	.364	1.022
B	.008	.044	.123
K	1.551	8.653	24.314
N	2.648	14.383	39.928

Generally, the 30-foot-high trees had a lower percentage of mineral content than the 10-foot-high trees.

Hergert et al.[1] found that stemwood ash content of three hardwood species varied considerably according to geographic location, as follows (table 6-1):

Species and geographic location	Ash content
	Percent
Elm, American	
Georgia	0.8, 0.3
Tennessee	.5
Hickory, mockernut	
Georgia	1.1
Tennessee	.4
Oak, white	
Georgia	1.0
Tennessee	.2

In a study of Louisiana **sweetgum** stemwood from bottomland (along the Mississippi River near Baton Rouge) and upland (near St. Francisville), Choong et al. (1974) found no between-site differences in ash or mineral contents. Bourgeois (1964) sampled sweetgum from seven areas in Louisiana; five of the areas were east of the Mississippi River, but one was centrally located and one was in the north close to the Arkansas border. He found significant differences among geographic locations. Range in ash content was from 0.40 percent at the northernmost site to 0.47 percent at a site near Baton Rouge. Mineral contents of stemwood from these two locations was as follows:

Element	Near Arkansas border	Near Baton Rouge
	Percent of ovendry weight	
Calcium	0.083	0.112
Iron	.001	.002
Magnesium	.020	.035
Phosphorus	.009	.009
Potassium	.088	.082
Sodium	.001	.004

WITHIN-TREE VARIATION

Table 6-18 shows that in 6-inch pine site hardwoods, average ash content of branchwood (0.94 percent) exceeds that of stemwood (0.75 percent). The ash content of stembark and branchbark (7.87 and 6.76 percent, respectively) greatly exceeds that of branchwood and stemwood.

Mineral content in such trees also varies significantly with tissue, as follows (averages derived from table 6-19):

Mineral	Stemwood	Stembark	Branchwood	Branchbark
	Parts/million of ovendry weight			
Fe	67.2	135.4	65.4	120.5
Zn	10.5	34.6	11.7	41.7
Cu	5.1	13.0	6.8	12.4
Mn	89.8	567.8	120.3	596.1
Na	200.9	449.4	198.7	433.2
Mg	434.4	1,099.6	573.0	1,232.4
Ca	1,907.8	30,529.8	2,505.4	26,377.3
K	1,550.0	2,046.3	1,731.6	2,452.0
Al	47.2	174.7	49.7	146.0
P	194.2	344.4	338.0	498.8

Chase and Young (1978) found that foliage of very small trees of **white ash** and **northern red oak** contained up to eight times greater percentage of N, Ca, K, Mg, and P than other tree parts; stems had least percentage of these elements (table 6-20). Foliage of these species also had greatest percentages of B and Mn, while roots had greatest percentages of Al, Cu, Fe, and Zn; Mo percentages were greatest in foliage and roots and least in stem and branches (table 6-21).

Wardell and Hart (1973) found significant radial variations in mineral contents of **white oak** trees measuring about 6 inches in dbh. Sapwood had significantly greater mineral content than heartwood, as follows (potassium measured by flame photometry, other elements by optical emission spectroscopy):

Element	Sapwood	Heartwood
	Parts/million of O.D. weight	
Calcium	1,050	708
Magnesium	92	17
Manganese	74	19
Phosphorus	115	0
Potassium	1,312	900

The ratios of mineral content in sapwood compared to heartwood varied not only among elements but also between tissue types. As sapwood was converted to heartwood P, K, Mn, Mg, and Ca were translocated out of the dying cells for reuse by other living cells of the tree (table 6-22).

TABLE 6-20.—*Average content of N, Ca, K, Mg, and P in components of small white ash and northern red oak trees from Maine* (Chase and Young 1978)[1]

Element and tree component	White ash	Northern red oak
	Percent of ovendry weight	
Nitrogen		
Foliage	1.73	1.96
Branches	.29	.32
Stem	.22	.20
Roots	.29	.29
Calcium		
Foliage	.98	.78
Branches	.42	.65
Stem	.43	.46
Roots	.36	.62
Potassium		
Foliage	2.01	1.72
Branches	.37	.32
Stem	.26	.19
Roots	.45	.44
Magnesium		
Foliage	.26	.20
Branches	.07	.04
Stem	.05	.03
Roots	.12	.06
Phosphorus		
Foliage	.16	.16
Branches	.04	.05
Stem	.03	.02
Roots	.04	.11

[1] Based on a three-tree sample of each species. Trees measured 0.5 to 1.5 inches in dbh. Bark was not separated from wood of branches, stem, or roots.

TABLE 6-21.—*Average content of Al, B, Cu, Fe, Mn, Mo, and Zn in components of small white ash and northern red oak trees from Maine* (Chase and Young 1978)[1]

Element and tree component	White ash	Northern red oak
	Parts per million	
Aluminum		
Foliage	65	81
Branches	25	30
Stem	27	29
Roots	132	341
Boron		
Foliage	23	36
Branches	10	12
Stem	7	8
Roots	8	11
Copper		
Foliage	11	9
Branches	11	5
Stem	9	12
Roots	34	19
Iron		
Foliage	91	63
Branches	32	29
Stem	33	36
Roots	100	127
Manganese		
Foliage	28	464
Branches	9	203
Stem	7	135
Roots	5	44
Molybdenum		
Foliage	2	2
Branches	1	1
Stem	1	1
Roots	2	2
Zinc		
Foliage	21	27
Branches	42	16
Stem	57	17
Roots	89	56

[1] Based on a three-tree sample of each species. Trees measured 0.5 to 1.5 inches in dbh. Bark was not separated from wood of branches, stem, or roots.

TABLE 6-22.—*Ratio of five elements occurring in two tissues types in sapwood to that in the same tissues in heartwood of white oak wood* (Wardell and Hart 1973)[1]

Element	Multiseriate ray	Tissue between Multiseriate rays
	-Ratio of sapwood content to heartwood	
Phosphorus[2]	7.20	3.14
Magnesium[3]	4.47	4.02
Potassium[4]	2.91	1.40
Manganese[3]	1.72	1.90
Calcium[2]	1.09	1.38

[1] Element content measured by an electron microprobe analyzer-scanning microscope.

[2] Four-tree sample

[3] Three-tree sample

[4] Two-tree sample

Sachs et al. (1966) observed that ash content of northern red oak was greatest in nonstained sapwood (0.73 percent of ovendry weight), least in nonstained heartwood (0.32 percent), and intermediate in stained heartwood (0.46 percent).

Safford et al. (1974) found that discolored areas in red maple had higher concentrations of five minerals than clear wood of this species, as follows (average of five trees):

Element	Disclored wood	Clear wood
	$\mu g/cm^3$	
Calcium	252	218
Magnesium	62	39
Manganese	44	32
Potassium	844	186
Sodium	8	5

6-8 pH

Stemwood and bark of pine-site hardwoods vary considerably in acidity (or alkalinity). These among-species variations influence gluability—and adhesive formulations appropriate for the species, pulping reactions, reactions on contact with metals, formulations of appropriate finishes, and most aspects of utilization requiring chemical treatment. The commonly used measure of acidity or alkalinity is pH, i.e., the logarithm of the reciprocal of the hydrogen ion concentration, expressed in gram atoms per liter of a solution. pH 7 (0.0000001 gram atom of hydrogen ion per liter), the value for pure water, is regarded as neutral. pH values from 0 to 7 indicate acidity, and pH values from 7 to 14 indicate alkalinity.

Comparison of values given in the literature for wood and bark is made difficult by variations in methods of evaluation. Descriptions of methodology and results have been made by Rice 1961, Stamm 1961, Moore and Johnson 1967, McNamara et al. 1970, Chow et al. 1971, and Kubinsky and Ifju 1973a.

Manwiller[6], using the method of Moore and Johnson (1967), found significant variation in pH among pine-site hardwood species but little variation among tissue types (table 6-23), as follows:

Tissue	Average	Minimum	Maximum
	pH		
Wood			
Stemwood	5.18	4.35 northern red oak	5.74 American elm
Branchwood	5.29	5.03 post oak	5.68 hackberry
Bark			
Stembark	5.23	4.70 scarlet oak	5.64 American elm
Branchbark	5.16	4.82 scarlet oak	5.75 hackberry

Each value in table 6-23 is the average for 10 trees; trees were sampled in such a way that tissue specimens represented whole trees. Trees were cut during 1971 and 1972; samples for pH determination were stored at 70°F and 50 percent RH until May 1973, at which time pH was measured. Among-tree standard deviations varied from 0.08 to 0.51.

See chapter 14 for pH of roots.

TABLE 6-23.—*pH of stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites* [1,2] (Data from Manwiller[3])

Species	Stemwood[4]	Stembark[4]	Branchwood[5]	Branchbark[5]
	pH			
Ash, green	5.43 (.11)	5.31 (.18)	5.45 (.11)	5.23 (.10)
Ash, White	5.47 (.14)	5.55 (.32)	5.51 (.16)	5.27 (.15)
Elm, American	5.74 (.17)	5.64 (.24)	5.54 (.14)	5.57 (.17)
Elm, winged	5.56 (.27)	5.53 (.18)	5.34 (.23)	5.43 (.20)
Hackberry[6]	5.69 (.16)	5.62 (.29)	5.68 (.30)	5.75 (.21)
Hickory, sp.	5.66 (.20)	5.58 (.40)	5.63 (.27)	5.41 (.32)
Maple, red	5.36 (.15)	4.96 (.26)	5.38 (.28)	4.87 (.33)
Oak, black	4.64 (.36)	5.48 (.25)	5.22 (.26)	5.24 (.26)
Oak, blackjack	5.49 (.17)	4.93 (.36)	5.28 (.14)	4.86 (.26)
Oak, cherrybark	5.06 (.30)	5.35 (.14)	5.19 (.14)	5.29 (.17)
Oak, laurel	5.09 (.13)	5.00 (.40)	5.04 (.10)	5.05 (.15)
Oak, northern red	4.35 (.18)	4.92 (.14)	5.16 (.22)	5.03 (.12)

TABLE 6-23.—*pH of stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites* [1,2] (Data from Manwiller[3])—Continued

Species	Stemwood[4]	Stembark[4]	Branchwood[5]	Branchbark[5]
	pH			
Oak, post	4.90	5.09	5.03	5.03
	(.36)	(.20)	(.15)	(.33)
Oak, scarlet	4.50	4.70	5.05	4.82
	(.40)	(.31)	(.33)	(.34)
Oak, Shumard	4.64	5.08	5.11	4.94
	(.15)	(.34)	(.16)	(.15)
Oak, southern red	4.90	5.10	5.18	5.04
	(.32)	(.31)	(.35)	(.23)
Oak, water	5.14	5.13	5.21	5.05
	(.22)	(.37)	(.29)	(.19)
Oak, white	4.60	5.13	5.04	5.10
	(.19)	(.27)	(.18)	(.27)
Sweetbay	5.60	5.31	5.52	5.35
	(.16)	(.38)	(.15)	(.28)
Sweetgum	5.30	5.07	5.20	4.87
	(.15)	(.15)	(.10)	(.08)
Tupelo, black	5.38	5.36	5.25	5.08
	(.30)	(.51)	(.21)	(.27)
Yellow-poplar	5.43	5.20	5.45	5.24
	(.21)	(.39)	(.18)	(.23)

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[1] Values for wood or bark ground to pass a 40-mesh screen and suspended in water using a Beckman-Xpandomatic SS-2 pH meter.

[2] The first value tabulated under each heading is the average value for 10 trees; below (in parentheses) is the within-species standard deviation. See table 3-1 for description of trees sampled.

[3] Manwiller, F. G. Unpublished data in Final Report FS-SO-3201-1.41, dated March 19, 1981. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Pineville, La.

[4] From a point 6 inches above ground level to the point where the central stem could no longer be distinguished, or to a 0.5-inch minimum diameter outside bark.

[5] From the point of juncture with central stem extending out to a branch diameter of 0.5 inch outside bark.

[6] Mostly sugarberry.

The literature contains little data on radial variation of pH in stems of these species. McNamara et al. (1970) found that in woods with pronounced heartwood—such as the red and white oaks, heartwood was more acidic than sapwood.

Sachs et al. (1966) also observed that heartwood of northern red oak was more acidic than sapwood, as follows:

Tissue	pH
Nonstained heartwood	3.4 to 3.8
Stained heartwood	3.5 to 3.8
Nonstained sapwood	5.0 to 5.6

White and DeLuca (1978) found that the pH of hardwood bark, pine bark, and hardwood-pine sawdust declined significantly during 6 months of storage. Initial pH was in the range from 5 to 7, while ending pH was about 4 (fig. 11-14).

6-9 LITERATURE CITED

Abdusamatov, A., R. Ziyaev, and S. Yu. Yunusov. 1974. Alkaloids of *Liriodendron tulipifera* wood. Khim Prir. Soedin. 10(1):112-113.

Abdusamatov, A., R. Ziyaev, and S. Yu. Yunusov. 1975. Alkaloids of *Liriodendron tulipifera*. Khim. Prir. Soedin. 11(6):812-814.

Adams, G. A., and C. T. Bishop. 1960. Constitution of an arabinogalactan from maple sap. Can. J. Chem. 38:2380-2386.

Ahn, B. Z. 1974. Catechin trimer from oak bark. Arch. Pharm. 307(3):186-197. Weinheim, Ger.

Allison, F. E. 1965. Decomposition of wood and bark sawdusts in soil: Nitrogen requirement and effects on plants. 58 p. USDA, ARS Tech. Bull 1332.

Altman, P. L. and D. S. Dittmer. 1964. Biology data book. 615 p. Washington, D. C.: Fed. Am. Soc. Exp. Biol.

Arseneau, D. F., and J. M. Pepper. 1965. Comparative studies of isolated dioxane lignins. Pulp and Pap. Mag. Can. 66:T415-T421.

Baker, J. E., and D. M. Norris. 1967. A feeding stimulant for *Scolytus multistriatus* isolated from the bark of *Ulmus americana*. Ann. Entomol. Soc. Amer. 60:1213-1215.

Baldwin, S., R. A., Black, A. A. Andreasen, and S. L. Adams. 1967. Aromatic congener formation in maturation of alcohol distillates. Agric. Food Chem. 15:381-385.

Balsillie, D. 1972. The formation of heartwood phenols in red pine (*Pinus resinosa* Ait.) and white elm (*Ulmus americana* L.) Ph. D. thesis, Univ. Toronto, Ont.

Barton, D. H. R., D. S. Bhakuni, G. M. Chapman, and G. W. Kirby. 1967. Phenol oxidation and biosynthesis. Part XV. The biosynthesis of roemerine, anonaine, and mecambrine. J. Chem. Soc.: 2134-2140.

Bates, R. B., A. D. Brewer, B. R. Knights, and J. W. Rowe. 1968. Double bond configurations of 24-ethylidine sterols. Tetrahedron Lett. 59:6163-6167.

Bate-Smith, E. C. 1975. Phytochemistry of proanthocyanidins. Phytochem. 14:1107-1113.

Beebe, C. W., F. P. Luvisi, and M. L. Happich. 1953. Tennessee Valley oak bark as a source of tannin. J. Am. Leather Chem. Assoc. 48:32-41.

Bellas, T. E., R. G. Brownlee, and R. M. Silverstein. 1969. Synthesis of brevicomin, principal sex extractant in the frass of the female western pine beetle. Tetrahedron 25:5149-5153.

Bhargava, U. C. 1967. Pharmacology of ellagic acid from black walnut. Ph. D. thesis, Univ. Miss., 366 p.

Bhargava, U. C., and B. A. Westfall. 1968. Antitumor activity of *Juglas nigra* (black walnut) extractives. J. Pharm. Sci. 57(10):1674-1677.

Bhaskaran, T. A. and C. Schuerch. 1969. A study of nonvolatile hydrogenated maple wood lignin. Tappi 52:1948-1952.

Bick, I. R. C., J. Harley-Mason, N. Sheppard, and M. J. Vernengo. 1961. Structural correlations in the nuclear magnetic resonance spectra of bisbenzylisoquinoline and aporphine alkaloids. J. Chem. Soc.: 1896-1903.

Bilbruck, J. D. 1959. Toxicity of oak heartwood and oak heartwood water extracts to the oak wilt fungus. Plant Dis. Reporter 43(8):936-941.

Binotto, A. P., and W. K. Murphy. 1975. Season and height variation in extractives and cell wall components of chestnut oak bark. Wood Sci. 7(3):185-190.

Bjeldanes, L. F., and G. W. Chang. 1977. Mutagenic activity of quercetin and related compounds. Sci. 197:577-578.

Black, R. A., A. A. Rosen, and S. L. Adams. 1953. The chromatographic separation of hardwood extractive components giving color reactions with phloroglucinol. J. Am. Chem. Soc. 75:5344-5346.

Bleam, R. D. and J. M. Harkin. 1975. Lignins of hardwoods growing on southern pine sites. Wood Sci. 8:122-130.

Bolker, H. U. 1970. Delignification: A process of solubilization by breaking cross-links. (Abstr.) *In* Extended abstracts of papers presented at the 3rd Canadian Wood Chem. Symp., P. 71-72. (Vancouver, B. C., June 24-26.) Canadian Pulp and Pap. Assoc., and the Chem. Inst. of Canada

Bourgeois, G. W. 1964. Variation of ash content in sweetgum on different soil types. M. S. thesis. La. State Univ., Baton Rouge. 47 p.

Bowen, H. J. M. and D. Gibbons. 1963. Radioactivation analysis. 295 p. Oxford, England: Clarendon Press.

Brauns, F. E. and D. A. Brauns. 1960. The chemistry of lignin. 804 p. New York, N. Y.: Academic Press.

Briggs, L. H., R. C. Cambie, and R. A. F. Couch. 1968. Lirioresinol-C dimethyl ether, a diaxially substituted 3,7-dioxabicyclo [3,3,0] octane lignan from *Macropiper excelsum* (Forst. f.) Miq. J. Chem. Soc. (C):3042-3045.

Browning, B. L., Ed. 1963. The chemistry of wood. 689p. New York, N. Y.: Interscience Publ.

Browning, B. L. and I. H. Isenberg. 1952. Analytical data and their significance. *In* Wood chemistry. Vol. 2, pp. 1259-1277. Wise, L. E. and E. C. Jahn, eds. New York, N. Y.: Reinhold Publ. Corp.

Buchanan, M. A., and E. E. Dickey. 1960. Liriodenine, a nitrogen-containing pigment of yellow poplar heartwood (*Liriodendron tulipifera* L.). J. Org. Chem. 25:1389-1391.

Bylund, M. and A. Donetzhuber. 1968. [Semimicro determination of uronic acids.] Svensk Papperstidning 71(15):505-508.

Cernigliaro, G. J., and P. J. Kocienski. 1977. A synthesis of (-)-α-multistriatin. J. Org. Chem. 42:3622-3624.

Chang, Y. -P., and R. L. Mitchell. 1955. Chemical composition of common North American pulpwood barks. Tappi 38:315-320.

Chang, H. -M. and K. V. Sarkanen. 1973. Species variation in lignin. Effect of species on the rate of kraft delignification. Tappi 56(3):132-134.

Chase, A. J., and H. E. Young. 1978. Pulping, biomass, and nutrient studies of woody shrub and shrub sizes of tree species. Bull. 749. Life Sci. and Agric. Exp. Stn., Univ. Maine, Orono. 36 p.

Chen, C. -L. 1970. Constituents of *Quercus alba*. Phytochem. 9:1149.

Chen, C. R., J. L. Beal, R. W. Doskotch, L. A. Mitscher, and G. H. Svoboda. 1974. Phytochemical study of *Doryphora Sassafras*. II. Isolation of eleven crystalline alkaloids from the bark. Lloydia 37(3):493-500.

Chen, C. -L., and H. -M. Chang. 1978. Lignans and aporphine alkaloids in bark of *Liriodendron tulipifera*. Phytochem. 17:779-782.

Chen, C. -L., H. -M. Chang, and E. B. Cowling. 1976a. Aporphine alkaloids and lignans in heartwood of *Liriodendron tulipifera*. Phytochem. 15:547-550.

Chen, C. -L., H. -M. Chang, E. B. Cowling, C. -Y. . Huang Hsu, and R. P Gates. 1976b. Aporphine alkaloids and lignans formed in response to injury of sapwood in *Liriodendron tulipifera*. Phytochem. 15:1161-1167.

Choong, E. T., G. Abdullah, and J. Kowalczuk. 1976. Mineral content in bark and wood of selected delta hardwoods. LSU Wood Util. Notes No. 29, 4p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A&M Coll., Baton Rouge, La.

Choong, E. T., B. -Y. Chang, and J. Kowalczuk. 1974. Mineral content of wood and bark of sweetgum. LSU Wood Util. Notes No. 27, 4 p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A & M Coll., Baton Rouge, La.

Choong, E. T. and P. J. Fogg. 1976. Extractives content and cell-wall specific gravity in sweetgum. LSU Wood Util. Notes No. 30, 4 p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A & M Coll., Baton Rouge, La.

Chow, P., C. S. Walters, and J. K. Guiher. 1971. pH Measurements for pressure-refined plant-fiber residues. For. Prod. J. 21(12):50-51.

Clermont, L. P., and H. Schwartz. 1952. The chemical composition of Canadian woods. II. Pulp and Pap. Mag. Can. 53(6):142-143.

Cohen, J., W. von Langenthal, and W. I. Taylor. 1961. The alkaloids of *Liriodendron tulipifera* L. The structure and synthesis of the unnamed yellow alkaloid and the isolation of D-glaucine. J. Org. Chem. 26(10):4143-4144.

Cooke, G. B. 1961. Cork and the cork tree. Int. Ser. Monogr. Pure and Appl. Biol., Vol. 4. 121 p. New York, N. Y.: Pergamon Press.

Coscia, D. J., W. J. Schubert and F. F. Nord. 1961. Investigations on lignins and lignification. XXIII. Hydrogenation and hydrogenolysis of native and milled-wood lignins. Tappi 44:360-363.

Cowling, E. B., and T. K. Kirk. 1976. Properties of cellulose and lignocellulosic materials as substrates for enzymatic conversion processes. Biotechnol. and Bioeng. Symp. No. 6:95-123.

Crown, H. 1962. Storax is magic word for Alabama tree farmers. For. World, p. 31-32. (Oct. -Nov.)

Cutter, B. E., E. A. McGinnes, Jr., and D. H. McKown. 1980. Inorganic concentrations in selected woods and charcoals measured using NAA. Wood and Fiber 12:72-79.

Davis, D. J., D. Wiese, and J. P. Rosazza. 1977. Microbial transformations of glaucine. J. Chem. Soc. (Perkin I): 1-6.

Davis, R. E., Jr. 1973. The effect of rock type on the chemical composition of red oak and yellow poplar. (Abstr.) M.S. thesis. W. Va. Univ.

Davis, W. H., and W. S. Thompson. 1964. Influence of thermal treatments of short duration on the toughness and chemical composition of wood. For. Prod. J. 14:350-356.

De Stevens, G., and F. F. Nord. 1954. Studies on native lignin and lignification. Fortschritte der Chemischen Forschung 3:70-107.

Dickey, E. E. 1958. Liriodendrin, a new lignan diglucoside from the inner bark of yellow poplar (*Liriodendron tulipifera* L.). J. Org. Chem. 23:179-184.

Doskotch, R. W., S. K. Chatterji, and J. W. Peacock. 1970. Elm bark derived feeding stimulants for the smaller European elm bark beetle. Sci. 167:380-382.

Doskotch, R. W., and F. S. El-Feraly. 1969. Antitumor agents II. Tulipinolide, a new germacranolide sesquiterpene, and costunolide. Two cytotoxic substances from *Liriodendron tulipifera*. J. Pharm. Sci. 58:877-880.

Doskotch, R. W. and F. S. El-Feraly. 1970. Antitumor agents IV. Structure of tulipinolide and epitulipinolide cytotoxic sesquiterpenes from *Liriodendron tulipifera* L. J. Org. Chem. 35:1928-1936.

Doskotch, R. W., F. S. El-Feraly, E. H. Fairchild, and C. -T. Huang. 1976. Peroxyferolide: A cytotoxic germacranolide hydroperoxide from *Liriodendron tulipifera*. J. Chem. Soc. (Chem. Comm.): 402-403.

Doskotch, R. W., F. S. El-Feraly, E. H. Fairchild, and C. -T. Huang. 1977. Isolation and characterization of peroxyferolide, a hydroperoxy sesquiterpene lactone from *Liriodendron tulipifera*. J. Org. Chem. 42:3614-3618.

Doskotch, R. W., C. D. Hufford, and F. S. El-Feraly. 1972a. Antitumor agents. VI. Sesquiterpene lactones tulipinolide and epitulipinolide from *Liriodendron tulipifera*. J. Org. Chem. 37:2740-2744.

Doskotch, R. W., S. L. Keeley, Jr., and C. D. Hufford. 1972b. Lipiferolide, a cytotoxic germacranolide, and γ-liriodenolide, two new sesquiterpene lactones from *Liriodendron tulipifera*. J. Chem. Soc. (Chem. Comm.): 1137-1138.

Doskotch, R. W., S. L. Keeley, Jr., and C. D. Hufford. 1972b. Lipiferolide, a cytotoxic germacranolide, and γ-liriodenolide, two new sesquiterpene lactones from *Liriodendron tulipifera*. J. Chem. Soc. (Chem. Comm.): 1137-1138.

Doskotch, R. W., S. L. Keeley, Jr., C. D. Hufford, and F. S. El-Feraly. 1975. New sesquiterpene lactones from *Liriodendron tulipifera*. Phytochem. 14:769-773.

Ekimova, T., N. Gerasimova, and M. Pesheva. 1964. Determination of the influence of sulfites on the extraction of tannins from oakwood (*Quercus conferta*) and oak bark (*Quercus sessiliflora*) and on the quality of extracts obtained. Khim. -Ind. 36(3):90-95. Sofia.

Enkvist, T. 1975. Phenolics and other organic chemicals from kraft black liquors by disproportionation and cracking reactions. *In* Proc. of the 8th cellulose conf. I. Wood chemicals—a future challenge. Appl. Polym. Symp. No. 28, pp. 285-295. T. E. Timell, ed. New York, N. Y.: John Wiley & Sons.

Erickson, M., G. E. Miksche, and I. Somfai. 1973. (Characterization of angiosperm lignins by oxidative degradation. I. Dicotyledons.) Holzforsch. 27(4):113-117.

Falkehag, S. I. 1975. Lignin in materials. *In* Proc. of the 8th cellulose conf. I. Wood chemicals—a future challenge. Appl. Polym. Symp. No. 28, pp. 247-257. T. E. Timell, ed. New York, N.Y.: John Wiley & Sons.

Farnsworth, N. R., R. N. Blomster, M. W. Quimby, and J. W. Schermerhorn, eds. 1969-1974. The Lynn index. A bibliography of phytochemistry. Vols. VI-VIII. 412 p. Coll. Pharm. Univer. Ill., Chicago, Ill. 60612.

Fengel, D. and D. Grosser. 1975. (Chemical composition of softwoods and hardwoods—a bibliographical review.) Holz als Roh- und Werkstoff 33:32-34.

Fergus, B. J. and D. A. I. Goring. 1970a. The location of guaiacyl and syringyl lignins in birch xylem tissue. Holzforschung. 24:113-117.

Fergus, G. J., and D. A. I. Goring. 1970b. The distribution of lignin in birch wood as determined by ultraviolet microscopy. Holzforschung 24:118-124.

Fieser, L. F., and M. Fieser. 1959. Steroids. New York, N.Y.: Reinhold Publ. Corp.

Fracheboud, M. , J. W. Rowe, R. W. Scott, S. M. Fanega, A. J. Buhl, and J. K. Toda. 1968. New sesquiterpenes from yellow wood of slippery elm. For. Prod. J. 18:37-40.

Frei, J. K. 1972. Effect of bark extractives on orchids. Ph. D. thesis, Univ. of Miami, Miami, Fla.

Freudenberg, K. , and A. C. Neish. 1968. Constitution and biosynthesis of lignin. New York, N. Y.: Springer-Verlag. 129 p.

Fujimoto, H. and T. Higuchi. 1977a. Lignans from the bark of yellow poplar (*Liriodendron tulipifera* L.). J. Jap. Wood Res. Soc. 23:405-410.

Fujimoto, H. , and T. Higuchi. 1977b. Biosynthesis of liriodendron by *Liriodendron tulipifera*. Wood Res. Bull. , Inst. , Kyoto Univ. , 62, p. 1-10.

Fujita, M. , H. Itokawa, and Y. Sashida. 1973. Components of *Magnolia obovata*. III. Occurrence of magnolol and honokiol in *M. obovata* and other allied plants. J. Pharm. Soc. Japan 93(4):429-434.

Gerry E. 1921. American storax production: Results of different methods of tapping red gum trees. J. For. 19:1-10.

Gilbert, B. L. , J. E. Baker, and D. M. Norris. 1967. Juglone (5-Hydroxy-1, 4-Napthoquinone) from *Carya ovata*, a deterrent to feeding by *Scolytus multistriatus*. J. Insect Physiol. 13:1453-1459.

Gilbert, B. L., and D. M. Norris. 1968. A chemical basis for bark beetle (*Scolytus*) distinction between host and nonhost trees. J. Insect Physiol. 14:1063-1068.

Göhre, K. and E. Wagenknecht. 1955. Die Roteiche und ihr Holz. 300 p. Berlin: Deutscher Bauernverlag.

Goldstein, I. S. 1975. Perspectives on production of phenols and phenolic acids from lignin and bark. *In* Proc. of the 8th cellulose conf. I. Wood chemicals—a future challenge. Appl. Polym. Symp. No. 28, p. 259-267. (T. E. Timell, ed.) John Wiley and Sons, New York.

Goring, D. A. I. , and T. E. Timell. 1962. Molecular weight of native celluloses. Tappi 43:454-460.

Goto, T. , H. Harada, and H. Saiki. 1978. Fine structure of cellulose microfibrils in poplar gelatinous layer and valonia. Wood Sci. and Technol. 12:223-231.

Gottlieb, O. R. 1972. Chemosystematics of Lauraceae. Phytochem. 11:1537-1570.

Grushnikov, O. P. , and N. N. Shorygina. 1970. [The present state of the problem of lignin-carbohydrate bonds in plant tissues.] Russian Chem. Rev. 39(8):684-694.

Guenther, E. 1952. The essential oils. Vol. 5. p. 254. New York, N.Y.: van Nostrand.

Hanna, R. B. and W. A. Côté, Jr. 1974. The sub-elementary fibril of plant cell wall cellulose. Cytobiol. 10(1):102-116.

Happich, M. L. , C. W. Beebe, and J. S. Rogers. 1954. Tannin evaluation of one hundred sixty-three species of plants. J. Am. Leather Chem. Assoc. 49:760-773.

Haq, S. , and G. A. Adams. 1961. Oligosaccharides from the sap of sugar maple. Can. J. Chem. 39:1165-1170.

Harborne, J. B. 1977. Flavonoids and the evolution of the angiosperms. Biochem. Syst. Ecol. 5:7-22.

Harkin, J. M. 1967. Lignin: a natural polymeric product of phenol oxidation. *In* oxidative coupling of phenols, pp. 243-321. W. I. Taylor and A. R. Battersby, pp. 243-321. New York, N. Y.: Marcel Dekker, Inc.

Harkin, J. M. 1973. Lignin *In* Chemistry and biochemistry of herbage. R. W. Bailey and G. W. Butler (eds.). Vol. 1, chap. 7, pp. 323-373. New York, N. Y.: Academic Press.

Harkin, J. M. and J. R. Obst. 1973. Lignification in trees: indication of exclusive peroxidase participation. Sci. 180:296-298.

Harlow, W. M. and L. E. Wise. 1928. The chemistry of wood. I. Analysis of wood rays in two hardwoods. J. of Ind. Eng. Chem. 20(7):720-722.

Haslam, E. 1977. Symmetry and promiscuity in procyanidin biochemistry. Phytochem. 16:1625-1640.

Haslam, E., C. T. Opie, and L. J. Porter. 1977. Procyanidin metabolism—A hypothesis. Phytochem. 16:99-102.

Hass, H. B. 1977. Leaves of autumn. Chemtech 7(9):525-528.

Hathway, D. E. 1958. Oak-bark tannins. Biochem. J. 70:34-42.

Hathway, D. E. 1959. Experiments on the origin of oak-bark tannin. Biochem. J. 71:533-537.

Hegnauer, R. 1964-1973. Chemotaxonomie der Pflanzen, Vols. 3-6. Birkhaeuser Verlag, Basel and Stuttgart.

Hemingway, R. W. In press. Plant phenolic compounds. *In* Handbook of biosolar resources, Vol. IV, Resource Products/Applications, C. R. Keim, F. Shafizadeh, ed. CRC Press.

Hergert, H. L. 1977. Secondary lignification in conifer trees. *In* Cellulose chemistry and technology, pp. 227-243. J. C. Arthur, ed. ACS Symp. Ser. No. 48. Washington, D. C.: ACS.

Herrick, F. W. and H. L. Hergert. 1977. Utilization of chemicals from wood: retrospect and prospect. *In* Recent Adv. Phytochem 11:443-515, proc. 16th annu. meet. Phytochem. Soc. N. Am. , Plenum Press.

Hoover, J. D. , S. H. Wender, and E. G. Smith. 1977. Effect of phenolic compounds on glucose-6-phosphate dehydrogenase isoenzymes. Phytochem. 16:199-201.

Hsu, O. H. -H. and W. G. Glasser. 1975. Polyurethane foams from carboxylated lignins. *In* Proc. of the 8th cellulose conf. I. Wood chemicals— a future challenge. Appl. Polym. Symp. No. 28, pp. 297-307. T. E. Timell, ed. New York, N. Y.: John Wiley & Sons.

Huang Hsu, C. -Y. 1976. M. S. Thesis, North Carolina State University, Raleigh.

Hufford, C. D. 1976. Four new N-acetylnoraporphine alkaloids from *Liriodendron tulipifera*. Phytochem. 15:1169-1171.

Hufford, C. D. , and J. J. Funderburk. 1974. Nonbasic aporphine alkaloids from *Liriodendron tulipifera*. J. Pharm. Sci. 63(8):1338-1339.

Hufford, C. D. , M. J. Funderburk, J. M. Morgan, and L. W. Robertson. 1975. Two antimicrobial alkaloids from heartwood of *Liriodendron tulipifera* L. J. Pharm. Sci. 64(5):789-792.

Huneck, S. 1963. Triterpene acids of *Liquidambar orientalis*. Tetrahedron 19:479-482.

Isenberg, I. H. , M. A. Buchanan, and L. E. Wise. 1946, 1957. Extraneous components of American pulpwoods. Pap. Ind. 28:816-822; 38:945-946, 1042-1046, 1098.

Jeffrey, J. E. , E. V. Partlow, and W. J. Polglase. 1960. Chromatographic estimation of sugars in wood cellulose hydrolyzates. Anal. Chem. 32(13):1774-1777.

John M. K. 1970. Colorimetric determination of phosphorus in soil and plant material with ascorbic acid. Soil Sci. 109:214-220.

Jung, J. , and M. Hubbes. 1965. Growth inhibition of *Bacillus çereus* in vitro by glycosidal substances extracted from bark of *Fraxinus*. Can. J. Bot. 43:469-474.

Kawamura, I. and D. E. Bland. 1967. The lignins of *Eucalyptus* wood from tropical and temperate zones. Holzforsch. 21(3):65-74.

Kellogg, R. M. , C. B. R. Sastry and R. W. Wellwood. 1975. Relationships between cell-wall composition and cell-wall density. Wood and Fiber 7:170-177.

Kerr, A. J. and D. A. I. Goring. 1977. Lamellation of hemicellulose in the fiber wall of birch wood. Wood Sci. 9:136-139.

Kirk, T. K. , and K. Lundquist. 1970. Comparison of sound and white-rotted sapwood of sweetgum with respect to properties of the lignin and composition of extractives. Svensk Paperstidn. 73:294-306.

Klauditz, W. 1958. Uber den Ligningehalt des Festigungsgewebes einiger Laubholzer. Holzforsch. 12(6):161-166.

Klemola, A. 1958. Steam hydrolysis of birchwood, Part III. Investigation of low-molecular aromatic degradation products. Suomen Kemistilehti B 41:83-110, 152-167.

Krochmal, A. , R. S. Walters and R. M. Doughty. 1969. A guide to medicinal plants of Appalachia. U.S. Dep. Agric. For. Serv. , Res. Pap. NE-138.

Kubinsky, E. and G. Ifju. 1973a. A simple and fast method of pH measurement for wood. For. Prod. J. 23(2):54-56.

Kubinsky, E. and G. Ifju. 1973b. Influence of steaming on the properties of red oak. Part I. Structural and chemical changes. Wood Sci. 6:87-94.

Lanuza, J. M. de. 1964. The cork of *Quercus suber*. Inst. For. Invest. Exper. 35:7-138. Madrid.

Lengyel, P. 1964. (Investigations of different Hungarian woods.) Papiripar 8(6):189-196.

Lenz, B. L. 1968. Application of NMR spectroscopy to characterization of lignin. Tappi 51:511-519.

Levitin, N. 1970. The extractives of birch, aspen, elm, and maple: Review and discussion. Pulp Pap. Mag. Can 71(16):T361-T364.

Lindberg, J. J. , V. A. Era, and T. P. Jauhiainen. 1975. Lignin as a raw material for synthetic polymers. *In* Proc. of the 8th cellulose conf. I. Wood chemicals—a future challenge. Appl. Polym. Symp. No. 28, p. 269-275. (T. E. Timell, ed.) John Wiley and Sons, New York.

Mahood, S. A., and E. Gerry. 1921. The production of American storax. Drug. Cir., 3 p. (Jan.).

Mark, R. E. (n. d.) Molecular and cell wall structure of wood. An educational module. Empire State Paper Research Institute, State Univ. New York, Coll. Environ. Sci. and For., Syracuse.

Masaki, N., M. Hirabayashi, K. Fuji, K. Osaki, and H. Inouye. 1967. Monoterpene glycosides. V. The X-ray investigation of the monotropein molecule. Tetrahedron Lett. (25):2367-2370.

Maslen, E. N., C. Nockolds, and M. Paton. 1962. The stereochemistry of lirioresinol-B. Aust. J. Chem. 15:161-162.

Masuda, M., and K. Nishimura. 1971. Branched nonalactones from some *Quercus* species. Phytochem. 10:1401-1402.

Mayer, W., H. Seitz, J. C. Jochims, K. Schauerte, and G. Schilling. 1971. Tanning compounds from the chestnut and oak wood. VI. Structure of vescalagin. Justus Liebigs Ann. Chem. 751:60-68.

McGinnes, E. A., Jr. and R. A. Ralston. 1967. Growth-quality evaluation of black and scarlet oak grown in Missouri. Agric. Exp. Stn. Res. Bull. 912, 15 p. Univ. of Mo., Coll. of Agric., Columbia, Mo.

McGinnes, E. A., Jr. and K. Y-t. Wu. 1973. Intra-incremental chemical studies of ring shake in scarlet oak. Wood Sci. 5:287-294.

McGovern, J. N. and G. H. Chidester. 1948. Semichemical and sulfite pulping experiments and production of corrugating boards from blackjack oak. U.S. Dep. Agric. For. Serv., FPL Rep. No. D1414. 10p. For. Prod. Lab., Madison, Wis.

McGovern, J. N., E. L. Keller, and J. S. Martin. 1949. Pulps and corrugating paperboards from woodland hickory. U.S. Dep. Agric. For. Serv., FPL Rep. No. R1753. 13 p. For. Prod. Lab., Madison, Wis.

McNamara, W. S., C. E. Sullivan, and J. C. Higgins. 1970. pH measurements on northeastern woods. Wood Sci. 3:48-51.

Mell, C. D. 1939. Dyes and tans from the bark of the elm tree. Textile Color. 61:127.

Miller, J. G. and C. Schuerch. 1968. Synthesis of 2,4′-dihydroxy-3,3′-dimethoxy-5-ethylbibenzyl and its formation in lignin hydrogenation. Tappi 51:273-277.

Mitchell, R. L. 1955. Chemistry of hickory. U.S. Dep. Agric. For. Serv., Hickory Task Force Rep. No. 2, 12 p. Southeast. For. Exp. Stn., Asheville, N. C.

Moore, W. E. and D. B. Johnson. 1967. Procedures for the chemical analysis of wood and wood products. 292 p. U.S. Dep. Agric. For. Serv., For. Prod. Lab., Madison, Wis.

Morton, J. F. 1973. Plant products and occupational materials ingested by esophageal cancer victims in South Carolina. Q. J. Crude Drug Res. 13:2005-2022.

Mundy, B. P., R. D. Otzenberger, and A. R. DeBernardis. 1971. A synthesis of frontalin and brevicomin. J. Org. Chem. 36:2390.

Musha, Y. and D. A. I. Goring. 1974. Klason and acid-soluble lignin content of hardwoods. Wood Sci. 7:133-134.

Nair, G. V., and G. von Rudloff. 1960. Isolation of hyperin from red-osier dogwood. Can. J. Chem. 38(12):2531-2533.

National Council of the Paper Industry for Air and Steam Improvement, Inc. 1978. Information on the sulfur content of bark and its contribution to SO_2 emissions when burned as a fuel. Atmospheric Quality Improve. Bull. No. 96. NCASI, New York. 12 p.

Narayanan, V., and T. R. Seshadri. 1969. Chemical components of *Acer rubrum* wood and bark: Occurrence of procyanidin dimer and trimer. Indian J. Chem. 7(3):213-214.

Nelson, N. C. 1975. Extractives produced during heartwood formation in relation to amounts of parenchyma in *Jugland nigra* and *Quercus rubra*. Can. J. For. Res. 5(2):291-301.

Nimz, H. 1974. Beech lignin—proposal of a constitutional scheme. Angewandte Chemie (Int. ed.) 13:313-321.

Nitsch, J. P., and C. Nitsch. 1965. The presence of phytokinins and other growth substances in sap of *Acer saccharum* and *Vitis vinifera*. Bull. Soc. Bot. Fr. 112(1/2):11-18.

Norris, D. M. 1969. Mechanism of olfactory and gustatory stimulation of the nervous system in *Scolytus multistriatus*. Univ. Wis., For. Res. Notes. 147.

Norris, D. M. 1970. Quinol stimulation and quinone deterrency of gustation by *Scolytus multistriatus*. Ann. Entomol Soc. Amer. 63:476-478.

Oesch, F. 1969. The low molecular weight carbohydrates and polyphenols in the cambial sap of European beech and some other deciduous trees. Planta 87(4):360-380.

Omori, S. and A. Sakakibara. 1971. Hydrolysis of lignin with dioxane and water IX. Isolation of D, L-syringaresinol from hydrolytic products of Yachidamo (*Fraxinus mandshurica*). J. Jap. Wood Res. Soc. 17(10):464-467.

Omori, S. and A. Sakakibara. 1972. Isolation of a new lignan type compound with tetrahydrofuran nucleus and syringylglycerol-β-syringylglycerol ether from hydrolysis products of hardwood lignin. J. Jap. Wood Res. Soc. 18(11):577-578.

Omori, S. and A. Sakakibara. 1974. Isolation of new dimeric and trimeric compounds with lignin type linkages from the hydrolysis products of hardwood lignin. J. Jap. Wood Res. Soc. 20(1):48-49.

Pearce, G. T., W. E. Gore, R. M. Silverstein, J. W. Peacock, R. A. Cuthbert, G. N. Lanier, and J. B. Simeone. 1975. Chemical attractants for the smaller European elm bark beetle *Scolytus multristriatus* (Coleoptera, Scolytidae). J. Chem. Ecol. 1:115-124.

Pearl, I. A. 1974. Annual review of lignin chemistry. The Inst. of Pap. Chem., Appleton, Wis., 90 p.

Pennington, C. W. 1958. Tarahumar fish stupefaction plants. Econ. Bot. 12:95-102.

Pepper, J. M. 1958. Chemical aspects of hardwood lignins. Pulp and Pap. Mag. Can. 59(10):253-259.

Perem, E., and L. P. Clermont. 1962. Importance of tension wood in appraising wood quality. *In* Proc. IUFRO Congr. 13, Sect. 41, Pap. No. 2, 13 p.

Plouvier, V. 1952. New investigations on mannitol and syringoside of some Oleaceae. Compt. Rend. 234:1577-1579.

Plouvier, V. 1954. The heteroside composition of some *Fraxinus* (Oleaceae). Compt. Rend. 238:1835-1837.

Plouvier, V. 1964. L-inositol, L-quebrachitol, and D-pinitol in some botanical groups. The presence of shikimic acid in *Mammea americana*. Compt. Rend. 258:2921-2924.

Revol, J. -F., C. Gancet, and D. A. I. Goring. 1982. Orientation of cellulose crystallites in the S_2 layer of spruce and birch wood cell walls. Wood Sci. 14:120-126.

Rice, J. 1961. The pH of wood. Proc., Conf. on Theory of Wood Adhesion 2:2-4-15, Univ. Michigan, Ann Arbor.

Ritter, G. J. 1951. Hemicelluloses and cellulose of wood. U.S. Dep. Agric., Yearbook of Agric. 1950-1951: 798-802.

Ritter, G. J. and L. C. Fleck. 1922. Chemistry of wood. V. Results of analysis of some American woods. J. of Ind. and Eng. Chem. 14(11):1050-1054.

Ritter, G. J. and L. C. Fleck. 1923. Chemistry of wood. VI. The results of analysis of heartwood and sapwood of some American woods. J. of Ind. Eng. Chem. 15(10):1055-1056.

Ritter, G. J. and L. C. Fleck. 1926a. Chemistry of wood. VIII. Further studies of heartwood and sapwood. J. of Ind. and Eng. Chem. 18(6):556-577.

Ritter, G. J. and L. C. Fleck. 1926b. Chemistry of wood. IX. Springwood and summerwood. J. of Ind. and Eng. Chem. 18(6):608-609.

Roffael, W., and W. Rauch. 1974. Extractives of oak and their influence on bonding with alkaline phenol-formaldehyde resins. Holz als Roh- und Werkstoff 32(5):182-187.

Rolfe, G. L. 1974. Lead distribution in tree rings. For. Sci. 20:283-286.

Roux, D. G. 1972. Recent advances in the chemistry and chemical utilization of the natural condensed tannins. Phytochem. 11:1219-1230.

Rowe, J. W., and A. H. Conner. 1979. Extractives in eastern hardwoods—A review. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. FPL 18. 66 p.

Rowe, J. W., M. K. Seikel, D. N. Roy, and E. Jorgensen. 1972. Chemotaxonomy of *Ulmus*. Phytochem. 11:2513-2517.

Rowe, J. W., and J. K. Toda. 1969. Absolute configuration at C-4 of calamenene, 7-hydroxycalamenal, and the new naturally occurring sesquiterpene, 7-hydroxycalamenene. Chem. Ind. 922-923. London.

Russell, A., C. R. Vanneman, and W. E. Waddey. 1942-1945. Natural tanning materials of the Southeastern United States. Parts I-VIII. J. Am. Leather Chem. Assoc. 37:340-356; 38:30-34, 144-148, 235-238, 355-358; 39:173-178; 40:110-121, 422-426.

Sachs, I. B., J. C. Ward, and E. H. Bulgrin. 1966. Heartwood stain in red oak. Holz als Roh- und Werkstoff 24:489-497.

Safford, L. O., A. L. Shigo, and M. Ashley. 1974. Gradients of cation concentration in discolored wood of red maple. Can. J. of For. Res. 4:435-440.

Sandermann, W., and A. -W. Barghoorn. 1956. Gesundheitschädigende Hölzer. Holz als Roh- und Werkstoff 14(1):37-40; 14(3):87-94.

Sarkanen, K. V., and C. H. Ludwig. 1971. Lignins: Occurrence, formation, structure, and reactions 916 p. New York: Wiley Interscience.

Sarko, A. 1976. Crystalline polymorphs of cellulose: prediction of structure and properties. *In* Proc. of the 8th cellulose conf. II. Complete-tree utilization and biosynthesis and structure of cellulose. (T. E. Timell, ed.) Appl. Polym. Symp. No. 28:729-742. John Wiley and Sons, New York.

Sasaki, T. 1964. Components of pecan (*Carya pecan*) II. A new flavonol Caryatin isolated from the bark of pecan and its structure. J. Pharm. Soc. Jap. 84:47-51.

Schwartz, S. L. 1958. Hardborad from red alder and from a mixture of slow-growth southern oaks. U. S. Dep. Agric. For. Serv., FPL Rep. No. 2125. 20 p. For. Prod. Lab., Madison, Wis.

Sears, K. D., R. L. Casebier, H. L. Hergert, G. H. Stout, and L. E. McCandlish. 1974. The structure of catechinic acid. A base rearrangement product of catechin. J. Org. Chem. 39(22):3244-3247.

Seikel, M. K., F. D. Hostettler, and G. J. Niemann. 1971. Phenolics of *Quercus rubra* wood. Phytochemistry 10:2249-2251.

Senear, F. E. 1933. Dermatitis due to woods. J. Am. Med. Assoc. 101(20):1527-1536.

Sentz, P. D., and C. -L. Chen. 1977. Liriodendronine, an oxoaporphine from discolored wood of *Liriodendron tulipifera*. Phytochem. 16:3015-2017.

Seshadri, T. R. 1973. An investigation of the phenolic constituents of certain woods and barks, including North American species and representatives of genera common to North America and India. (J. W. Rowe, USDA PL-480 Proj. FG-In-425, For. Prod. Lab., Madison, Wis.).

Shim, C. S. 1954. A study on the effect of water-soluble extractives upon physical properties of wood. Coll. Theseon. (Sci. nat.), Univ. Seoul No. 1:117-162.

Singleton, V. L. 1974. Some aspects of the wooden container as a factor in wine maturation. *In* Advances in Chemistry No. 137: Chemistry of winemaking. Am. Chem. Soc., Washington, D. C.

Smale, B. C., R. A. Wilson, and H. L. Keil. 1964. A survey of green plants for antimicrobial substances. (Abstr.) Phytopathol. 54(7):748.

Smelstorius, J. A. 1975. A rapid indirect method for determining the total polysaccharide content of wood and bark of an angiosperm. Holzforschung 29:32-36.

Smith, W. A. 1960. New storax operation started. Tex. For. News 39(4):4,6.

Soderquist, C. J. 1973. Juglone and allelopathy. J. Chem. Educ. 50(11):782-783.

Spencer, R. W., and E. T. Choong. 1977. Isolation and characterization of several extractives in the bark and wood of sweetgum. Holzforschung 31:25-31.

Stamm, A. J. 1961. A comparison of: three methods for determining the pH of wood and paper. For. Prod. J. 11:310-312.

Stanek, D. A. 1958. A study of the low-molecular weight phenols formed upon hydrolysis of aspenwood. Tappi 41:601-609.

Stewart, C. M. 1973. Complexes of glucuronoxylan, uronic acid and lignin in Eucalypt woods. Cellul. Chem. Technol. 7:691-701.

Stinson, E. E., C. J. Dooley, J. M. Purcell, and J. S. Ard. 1967. Quebrachitol—A new component of maple sap and sirup. J. Agric. Food Chem. 15(3):394-397.

Sudo, K. and A. Sakakibara. 1973. Hydrogenolysis of protolignin. VII. Isolation of D,L-syringaresinol, biphenyl, and diaryl propane from hardwood lignin. J. Jap. Wood Res. Soc. 19(4):165-169.

Sullivan, J. D. and I. B. Sachs. 1966. Research on cellulose morphology. For. Prod. J. 16(9):83-86.

Suty, L. and E. Golis. 1972. Chemical structure of beech lignin and its changes during water hydrolysis. Cellul. Chem. Technol. 6:485-491.

Taylor, W. I. 1961. The structure and synthesis of liriodenine, a new type of isoquinoline alkaloid. Tetrahedron 14:42-45.

Tattar, T. A., and A. E. Rich. 1973. Extractable phenols in clear, discolored and decayed woody tissues and bark of sugar maple and red maple. Phytopathol. 63(1):167-169.

Thomas, R. J. 1977. Wood: structure and chemical composition. *In* Wood technology: chemical aspects. ACS Symp. Ser. No. 43, pp. 1-23. I. S. Goldstein, ed.

Thompson, M. J., S. J. Louloudes, W. E. Robbins, J. A. Waters, J. A. Steele, and E. Nosettig. 1962. Identity of the "House fly sterol." Biochem. Biophys. Res. Comm. 9:113-119.

Thompson, R. S., D. Jacques, E. Haslam, and R. J. N. Tanner. 1972. Plant proanthocyanidins. Part I. Introduction; the isolation, structure, and distribution in nature of plant procyanidins. J. Chem. Soc. (Perkin I): 1387-1399.

Thor, E., and H. A. Core. 1972. Relation of fertilization, irrigation and site factors with radial growth and wood properties of yellow-poplar. *In* Abst., Proc. Sixth TAPPI For. Biol. Conf., Inst. Pap. Chem., Appleton, Wis. Abst. V-1. 2 p.

Timell, T. E. 1960. Isolation of hardwood glucomannans. Svensk Papperstid. 63(15):472-476.

Timell, T. E. 1964. Wood hemicelluloses. Part I. Advances in Carbohydrate Chem. 19:247-302.

Timell, T. E. 1965. Wood and bark polysaccharides. *In* Cellular ultrastructure of woody plants, pp. 127-156. W. A. Côté, Jr., ed. Syracuse, N. Y.: Syracuse Univ. Press.

Timell, T. E. 1967. Recent progress in the chemistry of wood hemicelluloses. Wood Sci. and Technol. 1:45-70.

Timell, T. E. 1969. The chemical composition of tension wood. Svensk Papperstidning 72:173-181.

Timell, T. E., C. P. J. Glaudemans, and J. K. Gillham. 1958. Recent studies on the polysaccharides of white birch and other hardwoods. Pulp and Pap. Manuf. Can. 59:242-252.

Tippin, T. (ed.) 1978. Principles of maintaining productivity on prepared sites. Symp. Proc., March 21-22, Jackson, Miss., 171 p. U. S. Dep. Agric. For. Serv., South. For. Exp. Stn., New Orleans.

Tomita, M., and H. Furukawa. 1962a. Studies on the alkaloids of magnoliaceous plants. XXVII. Alkaloids of *Liriodendron tulipifera* L. (1). J. Pharm. Soc. Jap. 82(4):616-618.

Tomita, M. and H. Furukawa. 1962b. Studies on the alkaloids of magnoliaceous plants. XXXIV. Alkaloids of *Liriodendron tulipifera* L. (2). J. Pharm. Soc. Jap. 82(8):1199-1202.

Venkateraman, K. 1977. Flavonoids, tannins, stilbenes, lignans, and quinones in some Indian forest trees. PL-480, Proj. A7-FS-70. [J. R. Rowe, For. Prod. Lab., Madison, Wis.]

Venverloo, C. J. 1971. The lignin of *Populus nigra* L. cv. "Italica" and some other *Salicaceae*. Holzforsch. 25(1):18-24.

Vick, C. B., and M. A. Taras. 1969. Stain in red oak paraquet flooring. For. Prod. J. 19(9):83-86.

Vite, J. P., R. Luehl, B. Gerken, and G. N. Lanier. 1976. Elm bark beetles: Bait test in the upper Rhine Valley using synthetic pheromones. Z. Pflanzenkr. Pflanzenschutz 83:166-171.

Vorher, W. and W. H. M. Schweers. 1975. Utilization of phenol lignin. *In* Proc. of the 8th cellulose conf. I. Wood chemicals—a future challenge. Appl. Polym. Symp. No. 28, pp. 277-284. T. E. Timell, ed. New York, N. Y.: John Wiley & Sons.

Walkup, J. H., R. I. Rush, and G. Haywood. 1956. The extractives of southern gum woods. Tappi 396:190A-193A.

Wardell, J. F. and J. H. Hart. 1973. Radial gradients of elements in white oak wood. Wood Sci. 5:298-303.

Warthen, D., E. L. Gooden, and M. Jacobson. 1969. Tumor inhibitors: Liriodenine, a cytotoxic alkaloid from *Annona glabra*. J. Pharm. Sci. 58(5):637-638.

Weinges, K., W. Baehr, W. Ebert, K. Goeritz, and H. D. Marx. 1969. Constitution, formation, and significance of flavonoid tannins. Fortschr. Chem. Org. Naturst. 27:158-260.

Westfall, B. A., R. L. Russell, and T. K. Auyong. 1961. Depressant agent from walnut hulls. Science 134: 1617-1618.

White, M. A., and P. A. DeLuca. 1978. Bulk storage effects on the fuel potential of sawmill residues. For. Prod. J. 28(11):24-29.

Willits, C. O. 1965. Maple sirup producers manual. Agric. Res. Serv. USDA Agric. Handb. 134. Repr. 1971, U. S. Govt. Print. Off., Washington, D. C.

Wise, L. E. and E. C. Jahn. 1952. Wood chemistry. 2nd ed. 688 p. New York, N. Y.: Reinhold Publ. Corp.

Wise, L. E. and J. Pickard. 1955. Analysis of tupelo woods. Tappi 38:618-619.

Wise, L. E. and E. K. Ratliff. 1947. Quantitative isolation of hemicelluloses and summative analysis of wood. Anal. Chem. 19(7):459-462.

Woods, B., and C. D. Calnan. 1976. Toxic woods. B. J. Derm 94(Suppl. 13):1-97.

Wu, K. Y-t. and E. A. McGinnes, Jr. 1974. Intra-incremental studies of methylation in scarlet oak. Wood Sci. 7:92-98.

Yamasaki, T., K. Hata, and T. Higuchi. 1973. Dehydrogenation polymer of sinapyl alcohol. J. Jap. Wood Res. Soc. 19(6):299-300.

Yean, W. Q., and D. A. I. Goring. 1970. Molecular properties of lignin from continuous flow extraction of wood. (Abstr.) *In* Extended abstracts of papers presented at the 3rd Canadian Wood Chem. Symp., p. 71-72. (Vancouver, B. C., June 24-26.) Canadian Pulp and Pap. Assoc., and the Chem. Inst. of Canada.

Young, H. E., and P. M. Carpenter. 1967. Weight, nutrient element, and productivity studies of seedlings and saplings of eight tree species in natural ecosystems. Tech. Bull. 28, Maine Agric. Exp. Stn., Univ. Maine, Orono. 39 p.

Young, H. E., and V. P. Guinn. 1966. Chemical elements in complete mature trees of seven species in Maine. Tappi 49:190-197.

Ziyaev, R., A. Abdusamatov, and S. Yu. Yunusov. 1973 a. Alkaloids of *Liriodendron tulipifera*. Khim. Prir. Soedin. 9(4):505-506.

Ziyaev, R., A. Abdusamatov, and S. Yu Yunusov. 1973b. D-Caaverine and the new alkaloid lirinidine from *Liriodendron tulipifera*. Khim. Prir. Soedin. 9(6):760-763.

Ziyaev, R., A. Abdusamatov, and S. Yu. Yunusov. 1973c. Lirinine, a new alkaloid from *Liriodendron tulipifera*. Khim. Prir. Soedin. 9(1):67-70.

Ziyaev, R., A. Abdusamatov, and S. Yu. Yunusov. 1974a. Alkaloids of *Liriodendron tulipifera*. Khim. Prir. Soedin., 10(1):108-109.

Ziyaev, R., A. Abdusamatov, and S. Yu. Yunusov. 1974b. D-Isolaureline, a new alkaloid from *Liriodendron tulipifera*. Khim. Prir. Soedin., 10(5):685.

Ziyaev, R., A. Abdusamatov, and S. Yu. Yunusov. 1975. The dynamics of the accumulation and mutual transformation of alkaloids in *Liriodendron tulipifera*. Khim. Prir. Soedin. 11(4):478-481.

7

Specific Gravity

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CHAPTER 7

Specific Gravity

Specific gravity, a unitless measure of density relating wood weight to the weight of water, is a simple and useful index to the suitability of wood for many important uses. It is closely correlated with the mechanical strength of wood—and is therefore a primary factor in the segregation of wood for high-strength lumber, posts, crossties, flooring, implement handles, and sports gear. Density, frequently expressed as specific gravity, largely determines pulp yield from a given volume of wood, i.e., a cord of high-density hardwood will yield significantly more pounds of pulp than an equal volume of low-density wood of the same species.

7-1 WOOD DENSITY AND SPECIFIC GRAVITY

Specific gravity of wood is not governed by a single factor. Length and diameter of cells, thickness of cell walls, proportions of tissue types, proportion of earlywood and latewood, percent of cellulose and lignin, amount and constituents of extractives, and amount of trace minerals all affect the density and specific gravity of wood.

Since wood normally contains some water, and its volume and gross weight both vary with changes in moisture content, density and specific gravity determinations are difficult (see section 7-7 for methodology). For many purposes, mass or weight and volume of samples are most conveniently measured at different moisture levels. When this is the case, values are meaningful only when the measurement conditions are identified.

Specific gravity is the mass (or weight) of wood substance per unit volume of the gross wood divided by the mass or weight density of water. The moisture content at which the gross volume of wood is measured must be specified, and, for general purposes, is usually green volume or ovendry volume.

Mathematically,

$$G = \frac{m_o}{V_s \rho} \qquad (7\text{-}1)$$

where:

G is specific gravity (unitless)

m_o is the ovendry weight of the wood

V_s is the volume of the wood at some specified moisture content

ρ is the density of water in units of m_o and V.

Specific gravity is unitless and is numerically the same, regardless of the measurement system used in its determination.

Density is the mass or weight of the wood and its contained water divided by the actual gross volume of the wood with its contained water.

Mathematically,

$$D = m/V \tag{7-2}$$

where:

D = density
m = mass or weight of wood and water
V = gross volume of the wood with its contained water

Numerical values of density are dependent on the measurement system used. In the metric system it is commonly expressed in grams per cubic centimeter or kilograms per cubic meter. In English units, it is usually expressed as pounds per cubic foot.

Density of wood (pounds per cubic foot) at a specified percentage moisture content (M) above fiber saturation can be computed from its specific gravity (G), based on unextracted ovendry weight and green volume as follows:

$$D = (1 + \frac{M}{100})(G)(62.43) \tag{7-3}$$

Thus the density of white oak having a specific gravity of 0.665 (unextracted ovendry weight and green volume basis) and a moisture content of 62 percent (of dry weight) is:

$$D = (1.62)(0.665)(62.43) = 67.26 \text{ pounds per cubic foot}$$

To calculate the density of wood at a moisture content below fiber saturation, the percentage volumetric shrinkage (S), between green volume and the volume at the moisture content in question must be known. The density (pounds per cubic foot) now becomes:

$$D = (1 + \frac{M}{100})(G)(62.43)/(1 - \frac{S}{100}) \tag{7-4}$$

Thus, given that white oak volumetric shrinkage from green to 10-percent moisture content is about 13 percent (derived from equations 8-4 and 8-5 with data from tables 8-4 and 8-10), white oak stemwood at 10-percent moisture content will have a density of:

$$D = (1.10)(0.665)(62.43)/(1 - 0.13) = 52.5 \text{ pounds per cubic foot}$$

Table 7-1 presents density values, at a range of moisture contents, for bark-free unextracted stemwood of hardwoods of indicated specific gravity from southern pine sites. Average densities of green stems and branches (with and without bark) of the hardwood species on pine sites are shown in table 7-2; green wood (bark-free) of the following species will likely sink if immersed in water:

Stemwood	Branchwood	
Winged elm	Black oak	Post oak
All of the oaks listed	Blackjack oak	Shumard oak
	Laurel oak	White oak

Green weights per cubic foot (a function of specific gravity and moisture content) vary not only with species, but within species and within trees (table 7-2A). Sections 7-4, 7-5, and 7-6 elaborate on the variations in specific gravity, while chapter 8 deals with variations in moisture content. Specific gravities presented throughout this chapter and in the remainder of the book are based on unextracted ovendry weight and green volume, unless otherwise noted.

Because weights per cubic foot, including bark, of very small trees and sawlogs are sometimes useful, additional data are presented in the following paragraphs. For bulk densities of wood with bark, and of bark only, see also tables 13-23 and 13-32.

Section 16-1 contains analyses, by species, of complete-tree and whole-tree biomass. See also table 27-97 and the tabulation immediately following Equation 27-23 in the opening pages of Chapter 27.

TABLE 7-1.—*Density of bark-free unextracted stemwood from hardwoods growing on southern pine sites related to specific gravity and moisture content.*[1]

Moisture content (percent of ovendry weight)	Specific gravity (ovendry weight, green volume basis)									
	.30	.35	.40	.45	.50	.55	.60	.65	.70	.75
	Pounds per cubic foot									
0.........	21.2	24.9	28.6	32.5	36.4	40.4	44.4	48.4	52.6	56.8
10.........	22.3	26.2	30.1	34.0	37.9	41.9	46.0	50.0	54.2	58.3
20.........	23.4	27.3	31.3	35.3	39.3	43.4	47.4	51.5	55.6	59.7
30.........	24.4	28.4	32.5	36.5	40.6	44.6	48.7	52.8	56.8	60.9
40.........	26.2	30.6	35.0	39.3	43.7	48.1	52.4	56.8	61.2	65.6
50.........	28.1	32.8	37.5	42.1	46.8	51.5	56.2	60.9	65.6	70.2
60.........	30.0	35.0	40.0	44.9	49.9	54.9	59.9	64.9	69.9	74.9
70.........	31.8	37.1	42.5	47.8	53.1	58.4	63.7	69.0	74.3	79.6
80.........	33.7	39.3	44.9	50.6	56.2	61.8	67.4	73.0	78.7	84.3
90.........	35.6	41.5	47.4	53.4	59.3	65.2	71.2	77.1	83.0	89.0
100.........	37.5	43.7	49.9	56.2	62.4	68.7	74.9	81.2	87.4	93.6
110.........	39.3	45.9	52.4	59.0	65.5	72.1	78.7	85.2	91.8	98.3
120.........	41.2	48.1	54.9	61.8	68.7	75.5	82.4	89.3	96.1	103.0
130.........	43.1	50.3	57.4	64.6	71.8	79.0	86.1	93.3	100.5	107.7

[1] Based on volumetric shrinkage data computed from equation 8-6. It is assumed that volumetric shrinkage is linear from 30- to 0-percent moisture content. The 22-species average for fiber saturation point (table 8-4) is 30 percent.

TABLE 7-2.—*Density of freshly felled (green) 6-inch hardwoods growing on southern pine sites* (Manwiller 1975, 1979)[1,2]

	Stem		Branches		
Species	Stemwood	Stem with bark	Branchwood	Branches with bark	Tree with bark
	Pounds per cubic foot				
Ash, green	51.6	50.7	51.0	51.7	50.7
Ash, white	53.6	51.0	51.0	51.5	51.1
Elm, American	58.7	56.8	54.2	51.9	56.4
Elm, winged	64.4	58.0	61.3	55.7	59.7
Hackberry	56.6	56.6	56.4	56.7	56.6
Hickory, true	60.8	60.0	56.2	55.6	59.7
Maple, red	52.6	53.2	55.0	55.0	53.3
Oak, black	65.5	64.1	63.0	61.3	63.7
Oak, blackjack	69.4	66.1	70.2	65.2	65.9
Oak, cherrybark	64.8	63.9	62.3	61.0	63.6
Oak, chestnut	—	—	—	—	—
Oak, laurel	63.4	63.2	62.9	62.0	62.9
Oak, northern red	64.1	63.6	59.3	58.3	63.2
Oak, post	68.1	63.3	64.8	58.6	62.9
Oak, scarlet	65.8	64.5	61.6	60.3	64.1
Oak, Shumard	66.0	65.0	62.4	61.3	64.7
Oak, southern red	64.7	62.9	61.1	59.0	62.5
Oak, water	63.6	63.0	61.6	60.4	62.8
Oak, white	67.2	65.3	62.9	59.9	65.0
Sweetbay	54.8	54.9	52.6	51.8	54.6
Sweetgum	62.3	59.2	58.8	57.5	59.0
Tupelo, black	59.3	56.8	57.7	56.2	56.8
Yellow-poplar	52.2	52.5	52.0	51.4	52.5

[1] Values tabulated are tree averages based on a sample of 10 trees (6-inch dbh) per species drawn from pine sites throughout the southern range of each species. They are derived from tables 7-7 and 8-2.

[2] See table 13-40 for density of bark.

TABLE 7-2A.—*Specific gravity*[1] *and green weight per cubic foot*[2] *of wood and bark of components of seven species of southern hardwood trees 6 to 22 inches in diameter* (Clark and Schroeder 1977; Clark et al. 1980abc; and personal communication with J.G. Schroeder, A. Clark III, and D.R. Phillips, November 1981)[1,2,3]

Tree component	Wood		Bark	
	Specific gravity	Density	Specific gravity	Density
		Pounds/cu ft		*Pounds/cu ft*
	CHESTNUT OAK FROM MOUNTAINS OF WESTERN NORTH CAROLINA			
Whole tree[4]	0.622 ± 0.019	65 ± 1.8	0.523 ± 0.028	53 ± 3.3
Stem (butt to 4-inch dib top)	.622 ± .021	66 ± 1.9	.533 ± .035	52 ± 3.6
Sawlog (butt to 8-inch dib top)	.625 ± .022	67 ± 2.1	.541 ± .035	54 ± 2.3
Pulpwood (8- to 4-inch dib top) .	.617 ± 0.25	64 ± 2.5	.529 ± .031	51 ± 3.2
Topwood (4- to 2-inch dib top)	.617 ± .033	63 ± 3.0	.523 ± .038	51 ± 4.4
Branches.	.619 ± .027	63 ± 2.1	.494 ± .031	54 ± 2.4
	NORTHERN RED OAK FROM WESTERN NORTH CAROLINA			
Whole tree	.581 ± .020	65 ± 1.5	.616 ± .028	62 ± 2.0
Stem (butt to 4-inch dib top)	.574 ± .021	65 ± 1.7	.631 ± .032	63 ± 2.3
Sawlog (butt to 8-inch dib top)	.568 ± .022	66 ± 1.5	.634 ± .038	63 ± 2.5
Pulpwood (8- to 4-inch dib top) .	.608 ± .026	65 ± 1.9	.658 ± .038	64 ± 2.2
Branches.	.605 ± .024	64 ± 1.9	.589 ± .046	61 ± 2.6
	SCARLET OAK FROM TENNESSEE CUMBERLAND PLATEAU			
Whole tree	.608 ± .022	67 ± 1.5	.611 ± .027	61 ± 2.7
Stem (butt to 4-inch dib top)	.595 ± .024	67 ± 1.7	.629 ± .031	62 ± 2.7
Sawlog (butt to 8-inch dib top)	.592 ± .028	68 ± 2.2	.624 ± .036	61 ± 3.2
Pulpwood (8- to 4-inch dib top) .	.618 ± .026	67 ± 1.9	.643 ± .033	63 ± 3.1
Topwood (4- to 2-inch dib top)	.630 ± .027	66 ± 1.9	.629 ± .041	62 ± 3.4
Branches.	.648 ± .027	66 ± 2.4	.572 ± .045	58 ± 4.5
	SOUTHERN RED OAK FROM THE HIGHLAND RIM OF TENNESSEE			
Whole tree	.604 ± .021	66 ± 1.5	.642 ± .035	59 ± 2.6
Stem (butt to 4-inch dib top)	.587 ± .022	65 ± 1.5	.652 ± .042	58 ± 3.0
Sawlog (butt to 8-inch dib top)	.587 ± .022	66 ± 1.7	.651 ± .046	58 ± 3.1
Pulpwood (8- to 4-inch dib top) .	.602 ± .023	65 ± 1.8	.668 ± .042	60 ± 3.5
Topwood (4- to 2-inch dib top)	.633 ± .033	65 ± 2.6	.667 ± .031	62 ± 3.5
Branches.	.659 ± .024	66 ± 1.8	.606 ± .044	58 ± 3.2
	WHITE OAK FROM WESTERN NORTH CAROLINA			
Whole tree	.615 ± .027	65 ± 1.8	.505 ± .039	54 ± 3.8
Stem (butt to 4-inch dib top)	.607 ± .032	65 ± 1.8	.522 ± .046	54 ± 4.8
Sawlog (butt to 8-inch dib top)	.606 ± .035	65 ± 2.2	.520 ± .050	54 ± 4.8
Pulpwood (8- to 4-inch dib top) .	.624 ± .032	64 ± 2.5	.535 ± .051	55 ± 4.8
Topwood (4- to 2-inch dib top)	.636 ± .029	65 ± 2.4	.531 ± .043	55 ± 3.6
Branches.	.632 ± .035	64 ± 2.7	.477 ± .043	55 ± 3.0
	SWEETGUM FROM THE GEORGIA PIEDMONT			
Whole tree	.467 ± .022	63 ± 2.3	.404 ± .069	48 ± 5.8
Stem (butt to 4-inch dib top)	.465 ± .022	64 ± 2.6	.408 ± .086	45 ± 7.1
Sawlog (butt to 8-inch dib top)	.468 ± .023	63 ± 2.8	439 ± .073	48 ± 5.7
Pulpwood (8- to 4-inch dib top) .	.474 ± .028	63 ± 2.5	.415 ± .092	47 ± 9.0
Topwood (4- to 2-inch dib top)	.477 ± .035	61 ± 3.1	.447 ± .058	55 ± 6.3
Branches.	.480 ± .021	60 ± 2.8	.400 ± .039	56 ± 2.9

TABLE 7-2A continued.—*Specific gravity*[1] *and green weight per cubic foot*[2] *of wood and bark of components of seven species of southern hardwood trees 6 to 22 inches in diameter* (Clark and Schroeder 1977; Clark et al. 1980abc; and personal communication with J.G. Schroeder, A. Clark III, and D.R. Phillips, November 1981)[1,2,3]

	Wood		Bark	
Tree component	Specific gravity	Density	Specific gravity	Density
		Pounds/cu ft		*Pounds/cu ft*
	YELLOW-POPLAR FROM WESTERN NORTH CAROLINA			
Whole tree	.407 ± .029	51.8 ± 3.5	.325 ± .028	49.1 ± 8.4
Stem (butt to 4-inch dib top)	.407 ± .030	51.8 ± 3.7	.332 ± .034	46.8 ± 8.4
Sawlog (butt to 8-inch dib top)	.406 ± .029	51.5 ± 3.8	.328 ± .035	46.1 ± 8.0
Pulpwood (8- to 4-inch dib top)	.413 ± .037	52.3 ± 4.6	.354 ± .027	49.3 ± 8.2
Topwood (4- to 2-inch dib top)	.419 ± .035	55.2 ± 4.4	.350 ± .035	54.8 ± 6.5
Branches	.424 ± .026	54.4 ± 3.9	285 ± .048	59.9 ± 3.1

[1] Based on green volume and ovendry weight.
[2] In freshly felled trees.
[3] Values are based on 24 to 36 trees of each species.
[4] Foliage-free above-ground portions.

Understory trees (18 to 44 years old and 1.0 to 4.9 inches in diameter (average 3.0 inches) from hardwood stands in the Piedmont of Georgia were higher in both green and dry weight (per cubic foot of green volume) than comparable trees from the mountains of North Carolina (table 7-3).

Timson (1975) developed somewhat similar information, but for saw logs harvested from March through November in western Maryland, West Virginia, and western Virginia. His results were summarized as follows (plus and minus values indicate 95-percent confidence interval):

Species	Green weight of wood and bark Lbs./cu/ ft. of entire log with bark
Ash, white	46 ± 2
Hickory, true	59 ± 1
Maple, red	53 ± 2
Oak, chestnut	59 ± 1
Oak, northern red	59 ± 1
Oak, white	57 ± 1
Tupelo, black	56 ± 3
Yellow-poplar	59 ± 1

TABLE 7-3—*Green and dry weights per cubic foot (green volume) of understory trees 1.0 to 4.9 inches in diameter, and bark percentages, by region and species* (Phillips and McClure 1976)

Species	Green weight[1]			Ovendry weight[1]			Proportion of bark, dry weight basis		
	Stem	Branches	Total tree	Stem	Branches	Total tree	Stem	Branches	Total tree
	pounds/cu ft						Percent		
MOUNTAINS (NORTH CAROLINA)									
Hickory, true	59.8	56.4	59.4	38.0	34.4	37.6	26.5	30.4	26.9
Maple, red	61.5	62.5	61.8	32.6	31.9	32.5	18.2	25.4	19.5
Oak, chestnut	64.1	62.7	63.8	38.1	36.0	37.8	23.9	31.0	24.8
Oak, white	62.2	61.4	62.1	37.0	35.3	36.9	21.4	32.3	22.9
Yellow-poplar	52.5	55.2	52.8	22.5	24.7	22.7	18.8	29.8	19.8
PIEDMONT (GEORGIA)									
Hickory, true	66.0	63.5	65.4	41.3	38.2	40.6	28.6	31.3	29.1
Maple, red	60.2	59.5	60.0	33.5	33.0	33.4	15.0	21.4	16.7
Oak, southern red	65.0	66.2	65.2	38.3	39.2	38.4	29.7	29.0	29.7
Oak, white	62.4	61.6	62.3	36.1	36.0	36.1	27.2	38.9	28.4
Sweetgum[2]	58.6	64.1	59.6	26.4	28.6	26.8	22.7	29.3	23.8
Yellow-poplar	59.0	59.6	59.1	24.6	25.5	24.8	21.6	32.6	23.8

[1] Includes bark.
[2] Computed from Phillips (1977).

7-2 CELL WALL DENSITY

The density of cell wall substance (as distinct from the cell wall which may contain voids) can be approximated from the proportion and specific gravities of its constituent components. *In situ* values would be preferable, but are not available. Specific gravities of prepared constituents, particularly hardwood hemicelluloses, are affected by method of preparation. Specific gravities of some or all constituents *in situ* may be greater than those of prepared constituents. The latter, when related by simple rule of mixtures to cell wall density, yield computed values slightly less than measured values Kellogg et al. 1975). Specific gravities for prepared constituents of hardwoods are tabulated as follows (after Beall 1972):

Material	Specific gravity	Proportion of extractive- and ash-free wood (see sect. 6-1)
		Percent
Alpha cellulose	1.520	43.1
Hemicellulose	1.457	31.2
Lignin	1.366	25.7
		100.0

Knowledge of cell wall density, and of void volume within the cell wall (probably not more than 4 percent), permits computation of the density of cell wall substance (Kellogg and Wangaard 1969; Kellogg et al. 1975). Cell wall density is most directly determined by measuring the volume of fluid displaced by a known mass of wood, but the measurement conditions must be stated, because displacement media vary in their ability to penetrate voids in the cell wall and in their interactions with wood.

Values for the density of wood substance should therefore be accompanied by reference to the measurement method as well as the condition of the wood, i.e., extracted or unextracted.

Table 7-4 is a summary of experimentally determined cell wall densities of southern hardwoods. The picnometer used in most of these experiments is a device for accurately measuring volume displacement of small specimens submerged in water or other liquid medium.

Kellogg et al. (1975) found that cell wall density of hardwoods and softwoods was closely correlated (fig. 7-1) with relative crystallinity of extracted wood meal determined following the X-ray technique described by El-osta and Wellwood (1972). The relationship of cell wall density of hardwoods to holocellulose yield was distinctly different from that for softwoods (fig. 7-2).

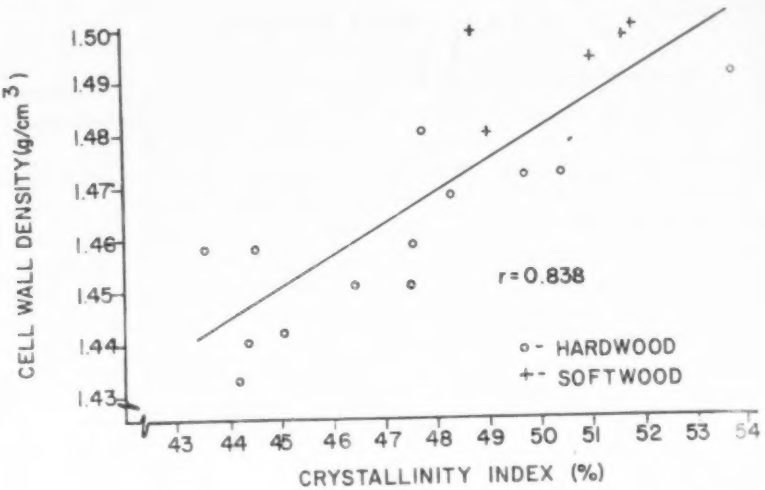

Figure 7-1.—Relationship between cell wall density and crystallinity index. (After Kellogg et al. 1975.)

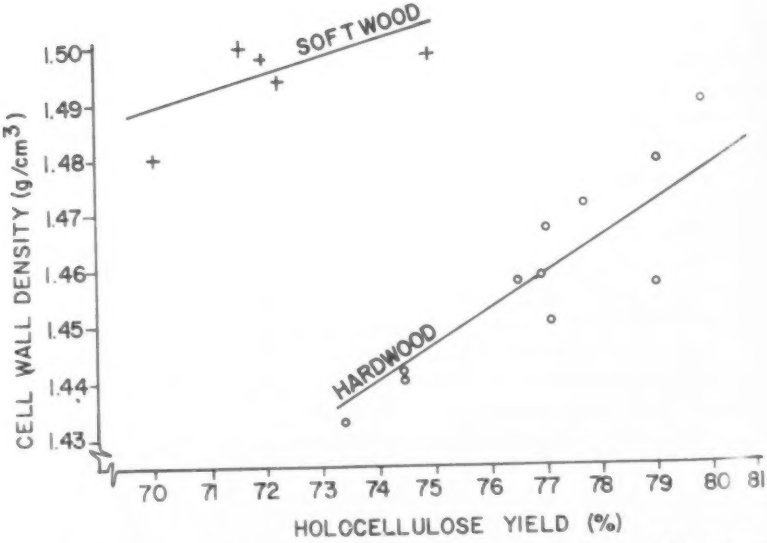

Figure 7-2.—Relationships between cell wall density and holocellulose yields in hardwoods and softwoods. (After Kellogg et al. 1975).

TABLE 7-4—*Cell wall density*

Species and density (g/cc)	Reference	Method
Ash, white (sapwood)		
1.508	Kellogg and Wangaard (1969)	Picnometric in water; extracted
Hickory, shagbark (sapwood)		
1.520	Kellogg and Wangaard (1969)	Picnometric in water; extracted
Maple, red (sapwood)		
1.528	Kellogg and Wangaard (1969)	Picnometric in water; extracted
Oak, northern red (sapwood)		
1.524	Kellogg and Wangaard (1969)	Picnometric in water; extracted
Oak, white		
1.540	Stamm (1929)	Picnometric in water; extracted
1.530	Wilfong (1966)	Picnometric in water; unextracted
1.525	Kellogg and Wangaard (1969)	Picnometric in water; extracted; sapwood
1.523	Wilfong (1966)	Picnometric in water; extracted
1.473	Stamm (1929)	Picnometric in non-polar liquid; extracted
1.439	Wilfong (1966)	Picnometric in non-polar liquid; unextracted
1.406	Wilfong (1966)	Picnometric in non-polar liquid; extracted
Sweetgum (sapwood)		
1.534	Choong and Fogg (1976)	Picnometric in water; unextracted
Sweetgum (heartwood)		
1.553	Choong and Fogg (1976)	Picnometric in water; unextracted
Yellow-poplar		
1.516	Stamm (1929)	Picnometric in water; extracted
1.508	Stamm (1929)	Helium displacement; extracted
Yellow-poplar (heartwood)		
1.531	Kellogg and Wangaard (1969)	Picnometric in water; extracted
1.527	Kellogg and Wangaard (1969)	Picnometric in water; unextracted
1.469	Kellogg and Wangaard (1969)	Picnometric in non-polar liquid; unextracted
1.465	Kellogg and Wangaard (1969)	Picnometric in non-polar liquid; extracted
1.458	Wilfong (1966)	Helium displacement; extracted
Yellow-poplar (sapwood)		
1.537	Wilfong (1966)	Picnometric in water; extracted
1.534	Wilfong (1966)	Picnometric in water; unextracted
1.522	Kellogg and Wangaard (1969)	Picnometric in water; extracted
1.462	Wilfong (1966)	Picnometric in non-polar liquid; extracted
1.461	Wilfong (1966)	Picnometric in non-polar liquid; unextracted

Density of the water-swollen cell wall can be determined optically by using a microscope to estimate the proportionate area of cell wall in a total cross-section of wood of known density (Smith 1965). Data determined in this manner, specific to five of the hardwoods of interest, have been published by Kellogg and Wangaard (1969), as follows:

Species	Density of water-swollen cell wall
	g/cc
Ash, white	1.058
Hickory, shagbark	1.119
Maple, red	.977
Oak, northern red	1.073
Oak, white	1.042

7-3 EFFECT OF EXTRACTIVE CONTENT ON SPECIFIC GRAVITY

Specific gravity is usually determined on unextracted wood. This practice results in an overestimate of the amount of wood substance present in samples of southern hardwoods because trees of these species contain significant amounts of extractives (tables 6-1 and 6-14).

In the 22 species studies, extractives (alcohol-benzene soluble) in stemwood averaged 4.7 percent of sample weight, and in branchwood 5.7 percent; sweetgum had minimum extractive content and blackjack oak maximum, as follows (table 6-14):

Species	Stemwood	Branchwood
	---Percent extractives---	
Sweetgum	2.3	3.1
Blackjack oak	6.9	7.8

With knowledge of percentage of extractive content (E) from table 6-14, extractive-free specific gravity (G_E) can be computed from the specific gravity of unextracted wood (G) as follows:

$$G_E = \frac{G}{1 + \frac{E}{100}} \tag{7-5}$$

In general, extractive content is a poor indicator of unextracted specific gravity of stemwood and branchwood of the 22 species studied. An equation of the form:

$$\hat{Y} = a + bx$$

where $\hat{Y}$ is specific gravity of unextracted wood, and x is the percentage of extractives, showed significant correlation for branchwood of only two species (winged elm and hackberry) and stemwood of only one (scarlet oak). In hackberry branchwood the correlation was negative; in winged elm branchwood and scarlet oak stemwood, the correlation was positive (table 7-5).

TABLE 7-5—*Straight-line regressions of specific gravity on percentage extractive content in 6-inch hardwoods from pine sites* (Manwiller 1979)[1]

Species and tissue	Coefficient of determination R^2	Standard error of estimate	Slope coefficient b	Intercept a	$\bar{x}^2$	$\bar{y}^3$
					%	
Elm, winged						
Branchwood	0.406	0.022	0.026	0.467	5.57	0.610
Hackberry						
Branchwood	.417	.035	−.047	.861	6.67	.551
Oak, scarlet						
Stemwood	.485	.020	.029	.449	6.07	.622

[1] All relationships tabulated are significant at 0.05 level.
[2] $\bar{x}$ = average percentage extractive content (alcohol-benzene ASTM D 1105-50T).
[3] $\bar{y}$ = average specific gravity, basis of unextracted ovendry weight and green volume.

7-4 SPECIES AVERAGE VALUES

Because of the size and continuously changing nature of the populations, it is difficult, if not impossible, to get figures that truly represent tree-average values of specific gravity for each species. Table 7-6 reflects specific gravity data accumulated by the U.S. Forest Products Laboratory over many years; values are averages for merchantable trees (generally 12-inch and larger) over all sites, and range from 0.40 for yellow-poplar to 0.66 for pignut hickory.

Because hardwoods on southern pine sites are typically small in diameter, species averages for 6-inch trees from such sites should be useful to readers of this text; values for above-ground portions of such trees are shown in table 7-7. The small number of trees of each species sampled (10) leaves the possibility of some error in estimating true South-wide means. In any event, the average value for a particular locality may well deviate considerably from the South-wide mean. Despite such limitations, the values in table 7-7 provide the best information currently available on specific gravity values for hardwoods growing on southern pine sites.

Stemwood averages ranged from a low of 0.40 for yellow-poplar to a high of 0.67 for white oak. Other species with low stemwood specific gravity (0.50 or less) include red maple, sweetbay, sweetgum, and black tupelo. Winged elm, the hickories, and all of the oaks except water and laurel oaks had stemwood specific gravities exceeding 0.60.

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TABLE 7-6—*Specific gravity of 23 eastern hardwoods commonly associated with southern pine* (Bendtsen and Ethington 1975)

Species	Specific gravity[1,2]
Ash, green	0.53
Ash, white	.55
Elm, American	.46
Elm, winged	.60
Hackberry	.49
Hickory, mockernut	.64
Hickory, pignut	.66
Hickory, shagbark	.64
Maple, red	.49
Oak, black	.56
Oak, blackjack	—
Oak, cherrybark	.61
Oak, chestnut[3]	.57
Oak, laurel	.56
Oak, northern red	.56
Oak, post	.60
Oak, scarlet	.60
Oak, Shumard	—
Oak, southern red	.52
Oak, water	.56
Oak, white	.60
Sweetbay	.45
Sweetgum	.46
Tupelo, black	.46
Yellow-poplar	.40

[1] Values are for merchantable bark-free stemwood from trees 12 inches and larger dbh.
[2] Based on unextracted ovendry weight and volume when green.
[3] From U.S. Department of Agriculture, Forest Service (1974, table 4-2).

Specific gravities for stemwood of 6-inch hickories, red maples, sweetgums, and yellow-poplars are about the same as for larger trees of these species (table 7-6); those for sweetbay are smaller, while for 17 other species the values for 6-inch trees are larger.

Because much of the hardwood volume on southern pine sites is in trees 1 to 5 inches in diameter, data for small trees of seven species are shown in table 7-8. These trees were in the understory of hardwood stands, but are included because no other data on very small trees are available. Except for the oaks, trees from the Georgia Piedmont averaged higher in specific gravity than trees from the North Carolina mountains. Yellow-poplar and sweetgum were lowest in wood specific gravity (0.37 to 0.45 for total tree), red maple was intermediate (0.51-0.52), and the oaks and hickory were highest (0.60-0.67). Understory trees of these species growing in the Piedmont of South Carolina are described on pages 1176 and 1202.

Data for trees of seven species, 6 to 22 inches in dbh, from North Carolina, Tennessee, and Georgia, are shown in table 7-2A.

TABLE 7-7—*Specific gravity (with standard deviation in parentheses) of 6-inch hardwoods growing on southern pine sites* Manwiller 1979)[1]

Species	Stem wood	Stem bark	Stem	Branch wood	Branch bark	Branch	Tree wood	Tree bark	Tree
Ash, green	0.561	0.407	0.536	0.556	0.450	0.532	0.560	0.411	0.535
	(.041)	(.045)	(.034)	(.035)	(.035)	(.027)	(.040)	(.042)	(.034)
Ash, white	.582	.397	.543	.559	.460	.533	.580	.402	.542
	(.037)	(.040)	(.032)	(.047)	(.060)	(.047)	(.037)	(.040)	(.032)
Elm, American	.536	.395	.515	.526	.356	.484	.535	.388	.512
	(.020)	(.039)	(.017)	(.035)	(.034)	(.025)	(.020)	(.037)	(.015)
Elm, winged	.623	.341	.557	.610	.369	.540	.622	.345	.574
	(.030)	(.030)	(.023)	(.031)	(.031)	(.014)	(.029)	(.029)	(.022)
Hackberry[2]	.525	.606	.532	.551	.541	.549	.527	.596	.534
	(.047)	(.056)	(.046)	(.048)	(.049)	(.042)	(.047)	(053)	(.045)
Hickory, true	.643	.522	.618	.607	.467	.567	.641	.516	.614
	(.051)	(.053)	(.049)	(.061)	(.059)	(.058)	(.051)	(.052)	(.049)
Maple, red	.496	.535	.500	.507	.469	.497	.495	.525	.498
	(.014)	(.027)	(.013)	(.013)	(.034)	(.078)	(.015)	(.023)	(.014)
Oak, black	.620	.612	.618	.648	.542	.624	.622	.606	.618
	(.022)	(.044)	(.022)	(.030)	(.042)	(.029)	(.021)	(.041)	(.021)
Oak, blackjack	.638	.642	.639	.706	.548	.662	.645	.631	.642
	(.024)	(.033)	(.018)	(.039)	(.031)	(.031)	(.027)	(.031)	(.018)
Oak, cherrybark	.623	.622	.623	.640	.520	.617	.624	.612	.622
	(.034)	(.052)	(.032)	(.024)	(.030)	(.024)	(.033)	(.048)	(.031)
Oak, chestnut	—	—	—	—	—	—	—	—	—
Oak, laurel	.582	.630	.589	.624	.521	.605	.586	.618	.590
	(.030)	(.043)	(.028)	(.034)	(.057)	(.029)	(.031)	(.038)	(.028)
Oak, northern red	.605	.644	.611	.597	.536	.583	.605	.636	.610
	(.034)	(.044)	(.034)	(.034)	(.050)	(.036)	(.034)	(.043)	(.034)
Oak, post	.659	.498	.626	.646	.438	.580	.658	.488	.622
	(.037)	(.055)	(.036)	(.048)	(.049)	(.039)	(.036)	(.054)	(.035)

See footnotes on next page.

TABLE 7-7 continued—*Specific gravity (with standard deviation in parentheses) of 6-inch hardwoods growing on southern pine sites* Manwiller 1979)[1]

Species	Stem wood	Stem bark	Stem	Branch wood	Branch bark	Branch	Tree wood	Tree bark	Tree
Oak, scarlet	.622 (.030)	.618 (.064)	.620 (.033)	.643 (.024)	.511 (.042)	.615 (.021)	.623 (.029)	.609 (.060)	.620 (.031)
Oak, Shumard	.625 (.040)	.644 (.062)	.627 (.042)	.643 (.027)	.540 (.060)	.622 (.025)	.627 (.038)	.636 (.058)	.627 (.041)
Oak, southern red	.609 (.020)	.601 (.039)	.607 (.022)	.621 (.026)	.504 (.033)	.592 (.026)	.610 (.020)	.593 (.036)	.606 (.021)
Oak, water	.587 (.034)	.628 (.052)	.593 (.032)	.604 (.025)	.508 (.046)	.585 (.020)	.588 (.033)	.618 (.049)	.593 (.031)
Oak, white	.665 (.039)	.543 (.055)	.648 (.039)	.637 (.039)	.488 (.027)	.596 (.030)	.664 (.039)	.537 (.051)	.645 (.038)
Sweetbay	.437 (.037)	.440 (.018)	.437 (.033)	.423 (.039)	.390 (.045)	.415 (.036)	.436 (.037)	.434 (.017)	.435 (.032)
Sweetgum	.453 (.018)	.369 (.047)	.439 (021)	.451 (.028)	.416 (.038)	.442 (.029)	.453 (.017)	.373 (.045)	.439 (.021)
Tupelo, black	.500 (.042)	.428 (.051)	.490 (.040)	.487 (.050)	.433 (.064)	.476 (.040)	.500 (.042)	.428 (.051)	.489 (.039)
Yellow-poplar	.395 (.032)	.390 (.035)	.394 (.028)	.406 (.036)	.335 (.035)	.389 (.028)	.395 (.032)	.385 (.031)	.394 (.027)

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[1] Based on ovendry unextracted weight and volume green; each value is an average of 10 trees. See tables 3-1 and 16-3 for additional tree data.

[2] Mostly sugarberry.

TABLE 7-8—*Specific gravity*[1] *and green moisture content of understory hardwoods 1.0 to 4.9 inches in diameter, by region and species* (Phillips 1977)

Species	Sample trees	Stem		Branches		Total tree		Moisture content wood and bark[2]		
		Wood	Wood and bark	Wood	Wood and bark	Wood	Wood and bark	Stem	Branches	Total tree
	Number	----------------------	*Specific gravity*	----------------------				----------	*Percent*	----------
				MOUNTAINS (NORTH CAROLINA)						
Hickory, true	12	0.63	0.61	0.58	0.55	0.62	0.60	58	64	58
Maple, red	12	.51	.52	.50	.51	.51	.52	89	96	91
Oak, chestnut	11	.63	.61	.59	.58	.63	.60	69	74	69
Oak, white	12	.62	.59	.59	.57	.62	.59	68	74	69
Yellow-poplar	12	.37	.36	.41	.40	.37	.36	132	128	132
				PIEDMONT (GEORGIA)						
Hickory, true	11	.67	.66	.64	.61	.67	.65	60	66	61
Maple, red	12	.52	.54	.51	.53	.52	.54	80	80	80
Oak, southern red	13	.59	.61	.62	.63	.60	.62	70	69	70
Oak, white	12	.61	.58	.61	.58	.61	.58	73	71	73
Sweetgum	12	.45	.42	.46	.46	.45	.43	122	124	122
Yellow-Poplar	12	.39	.39	.40	.41	.39	.40	141	134	139

[1] Unextracted, ovendry weight, green volume basis.
[2] Percentage of ovendry weight.

7-5 WITHIN-SPECIES VARIATION

Trees of a species vary in specific gravity because of variation in length and diameter of cells, thickness of cell walls, proportions of tissue types—particularly vessels (fig. 7-6 and 7-7) and rays (Taylor 1969), proportion of earlywood and latewood, percent of lignin and cellulose, amount and constituents of extractives, and amount of minerals. Because between-tree correlations of specific gravity with the foregoing factors are laborious and difficult to establish, literature on these correlations is scarce. Tree age, growth rate, and geographic location are readily available; investigations have usually correlated wood specific gravity with one or more of these factors. Discussions of such relationships follow, in alphabetical order by common names of the species. Values of specific gravity in this section and in the remainder of the book are based *on unextracted ovendry* weight and green volume, unless otherwise noted.

Few generalizations are applicable to all the hardwood species, but one relationship may generally hold true in ring-porous woods, i.e., trees that have maintained or increased their ring width from the pith outward contain wood of fairly uniform specific gravity and strength throughout; slowing of growth rate at any period of a tree's life produces lighter, weaker wood (Paul 1926). For several hardwood species (three oaks, black tupelo, sweetgum, yellow-poplar, and shagbark hickory), fast height growth was found associated with high specific gravity; but with mockernut hickory, the reverse was true (Taylor 1979).

ASH, GREEN

Ten 6-inch green ash trees from southern pine sites sampled Southwide, (table 3-1) had average specific gravity and between-tree variability as follows (table 7-7); "tree wood" means stemwood and branchwood combined:

Tree portion	Average	Standard deviation
Stemwood	0.561	0.041
Branchwood..................................	.556	.035
Tree wood	.560	.040

Sixty-one green ash trees 20 to 60 years of age (8- and 9-inch diameter classes) sampled from a variety of sites across the Piedmont and the Atlantic and Gulf Coastal Plains had average specific gravity of 0.55, with range from 0.48 to 0.60. Moisture content of these trees averaged 51 percent (dry weight basis) and ranged from 41 to 68 percent. When stratified by age class (table 7-9), no clear correlation of age, or growth rate with specific gravity was evident (Kellison and Zobel 1971).

Larger merchantable trees sampled throughout the species range in the United States (table 7-6) had lower stemwood specific gravity (0.53) than these 8- to 9-inch trees (0.55) or the 6-inch trees (0.56) from southern pine sites.

Butt sections of green ash from upland sites have specific gravity equal to or greater than that in upper stem sections (Paul 1963, p. 8); butt sections of green ash grown in periodically flooded areas, however, have significantly lower specific gravity than upper stem sections (Paul and Marts 1934, Pillow 1939).

TABLE 7-9.—*Bark free stemwood specific gravity and moisture content of green ash trees of five age classes from a variety of sites throughout the Piedmont and the Atlantic and Gulf Coastal Plains* (Kellison and Zobel 1971)[1]

Age class (years)	Diameter class	Total tree height	Merchantable height	Stemwood specific gravity[2]	Stemwood moisture content
	Inches	*Feet*			*Percent*
20	8	66	36	0.56	48
30	8	63	34	.56	53
40	8	62	34	.54	50
50	9	58	42	.53	50
60	9	68	35	.55	49

[1] Entire sample totalled 61 trees.

[2] Basis of unextracted ovendry weight and green volume.

When the trees described in table 7-9 were analyzed by type of site on which they grew, range of stemwood specific gravity (weighted-tree) was from 0.54 to 0.60; specific gravity tended to be inversely correlated with moisture content, as follows:

Site description and type	Specific gravity	Moisture content
		Percent
Red River bottom (Coastal)	0.54	53
Bottomland (Piedmont)	.54	48
Wet flat (Coastal Plain)	.56	57
Upland slope (Piedmont)	.58	52
Black River bottom (Coastal Plain)	.59	47
Muck swamp (Coastal Plain)	.60	45

ASH, WHITE

Ten-6-inch white ash trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.582	0.037
Branchwood	.559	.047
Tree wood	.580	.037

Stemwood of these 6-inch trees had higher specific gravity (0.58) than the average (table 7-6) stemwood from larger merchantabe white ash trees sampled throughout the United States range (0.55).

Very young ash trees also have stemwood of lower specific gravity. For example, 2-year-old trees averaged 0.46 with range from 0.39 to 0.51; stemwood moisture content ranged from 44 to 74 percent of dry weight, and averaged 54 percent (Jett and Zobel 1975).

In common with green ash, butt sections of white ash trees grown on uplands have specific gravity equal to or greater than upper stem sections; on sites flooded periodically, butt sections have lower specific gravity than upper stem sections (fig. 7-3). Pillow (1950) found that upland ash on well-drained hillside coves produced wood that is strong, stiff, and suitable for long, heavy handles of shovels and for oars. Creek-bottom trees and suppressed trees produced as heavy wood, but it was low in stiffness (fig. 7-3); wood from creek bottoms proved to be extremely high in shock resistance, however (fig. 7-4). Pillow concluded that creek-bottom ash is highly suitable for bent frames of tennis racquets or bent scythe handles, but should not be used for long handles that require stiffness (fig. 7-4).

White ash specific gravity varies substantially with geographic location. In its southern range, stemwood specific gravities ranged from a low of 0.495 for old-growth on clay loam at 3,300 feet elevation in West Virginia, to a high of 0.627 for 18- to 20-year-old plantation trees on alluvial sandy loam at 2,000 feet in North Carolina (table 7-10). Paul (1963) concluded that wood of uniformly high specific gravity results when rapid diameter growth is maintained throughout the life of white ash trees (fig. 7-5).

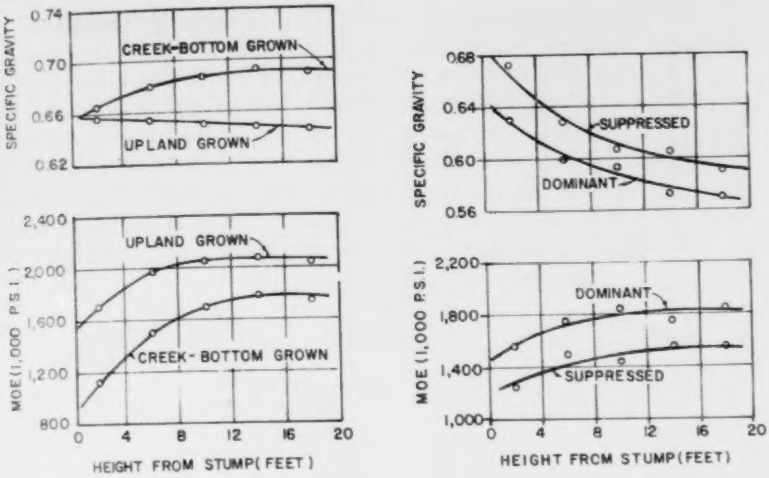

Figure 7-3.—Relation of average specific gravity (based on unextracted ovendry weight and air-dry volume) and modulus of elasticity to (left) height from stump of upland and creek-bottom open-growth ash, and (right) dominant and suppressed forest-grown ash. (Drawing after Pillow 1950.)

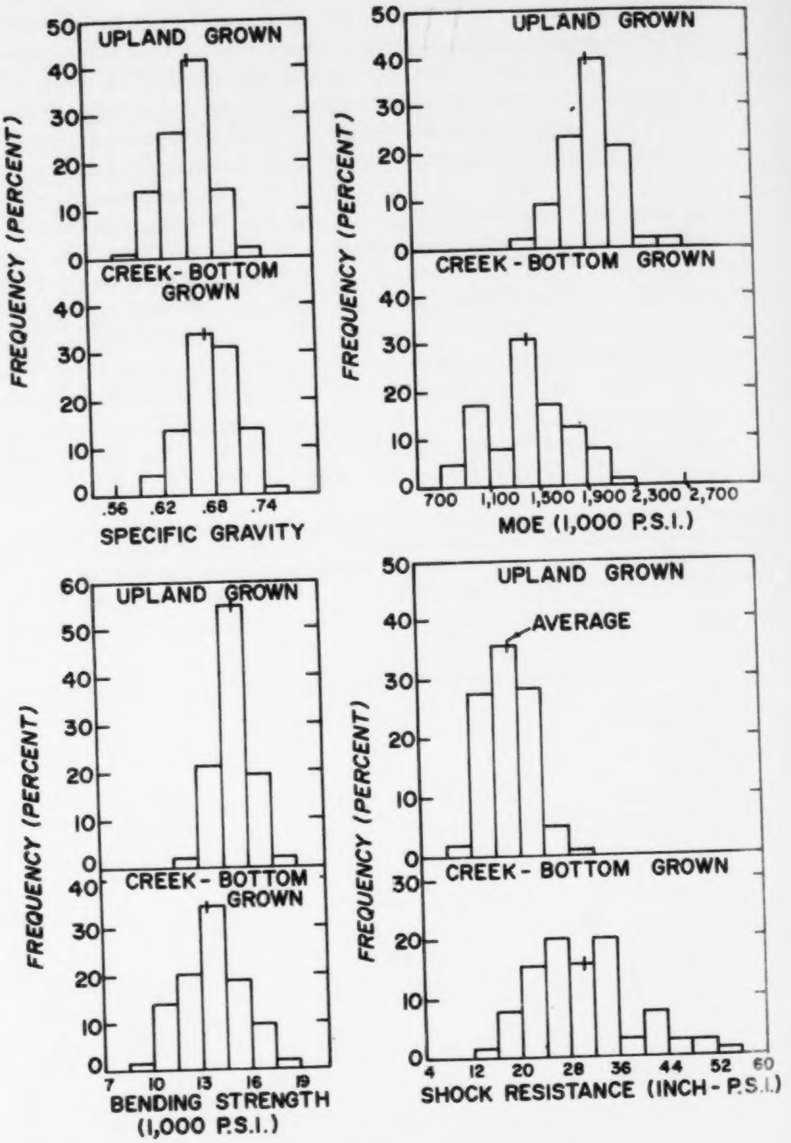

Figure 7-4.—Frequency distributions of specific gravity, modulus of elasticity, bending strength, and shock resistance of wood from open-grown ash trees sampled from upland and creek-bottom sites. (Drawing after Pillow 1950.)

In ring porous woods, circumstances that increase the proportion of latewood also increase wood specific gravity. Thus, as explained by Aldridge and Hudson (1954), woods such as ash can be grown either strong or weak by regulating the rate of growth. Rapid growth produces a greater proportion of latewood which is relatively free of large vessels (fig. 7-6). A large crown is essential for rapid growth and high latewood production. Any tree or stand may reach an age when growth rings are too narrow for high density; Aldridge and Hudson (1954) estimated that under correct growing conditions this age will be 60 to 70 years.

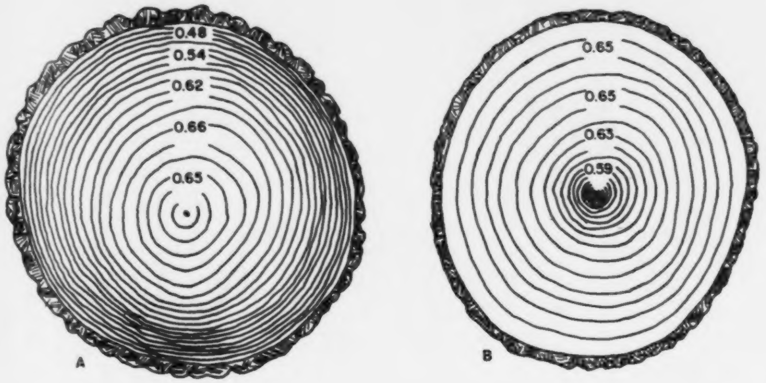

Figure 7-5.—Cross sections of white ash stems showing range of specific gravity and rate of growth. (A) Rapid growth when tree was young, and slow growth in later years when it was crowded in an unthinned stand. (B) Rapid growth throughout tree life resulting from thinning operations. Specific gravity values shown are based on ovendry weight and green volume. (Drawing after Paul 1963.)

TABLE 7-10.—*Specific gravity of stemwood 12 to 16 feet high in white ash from southern stands* (Paul 1963)

State and county	Elevation	Soil type	Character of stand	Sample trees	Range in age	Range in dbh	Average rings per inch	Specific gravity[1]
	Feet			*Number*	*Years*	*Inches*		
North Carolina Buncombe County	2,000	Alluvial sandy loam	Plantation	5	18–20	3–5	8.6	0.627[2]
Tennessee Scott County	1,750	Black sandy loam	Mixed ages, old growth	3	70–80	16–28	11.3	.596
Arkansas Pope County (Callan Hollow)	1,800	Stoney loam	Mixed ages, old growth	6	51–167	12–19	15.4	.582
North Carolina Buncombe County	3,500	Black loam	Mixed ages, old growth	7	41–143	8–14	15.8	.578
Tennessee Shelby County	50	Alluvial silty clay loam	Delta bottom land	6	41–119	11–19	10.8	.567
Arkansas Pope County (Sycamore Creek)	1,800	Stony loam	Mixed ages, old growth	7	63–133	7–20	16.9	.566

TABLE 7-10 continued—*Specific gravity of stemwood 12 to 16 feet high in white ash from southern stands* (Paul 1963)

State and county	Elevation	Soil type	Character of stand	Sample trees	Range in age	Range in dbh	Average rings per inch	Specific gravity[1]
	Feet			*Number*	*Years*	*Inches*		
Arkansas Stone County	1,100	Stony, gravelly loam	Old growth	5	90–122	14–18	14.8	.550
Tennessee Shelby County	250	Silt loam	Mixed ages, old growth	6	93–181	9–25	17.6	.541
West Virginia Pocahontas County	3,300	Clay loam	Old growth	5	156–303	18–31	17.2	.495

[1] Based on unextracted ovendry weight and green volume.

[2] These samples were taken at heights from 8 to 16 feet above ground level.

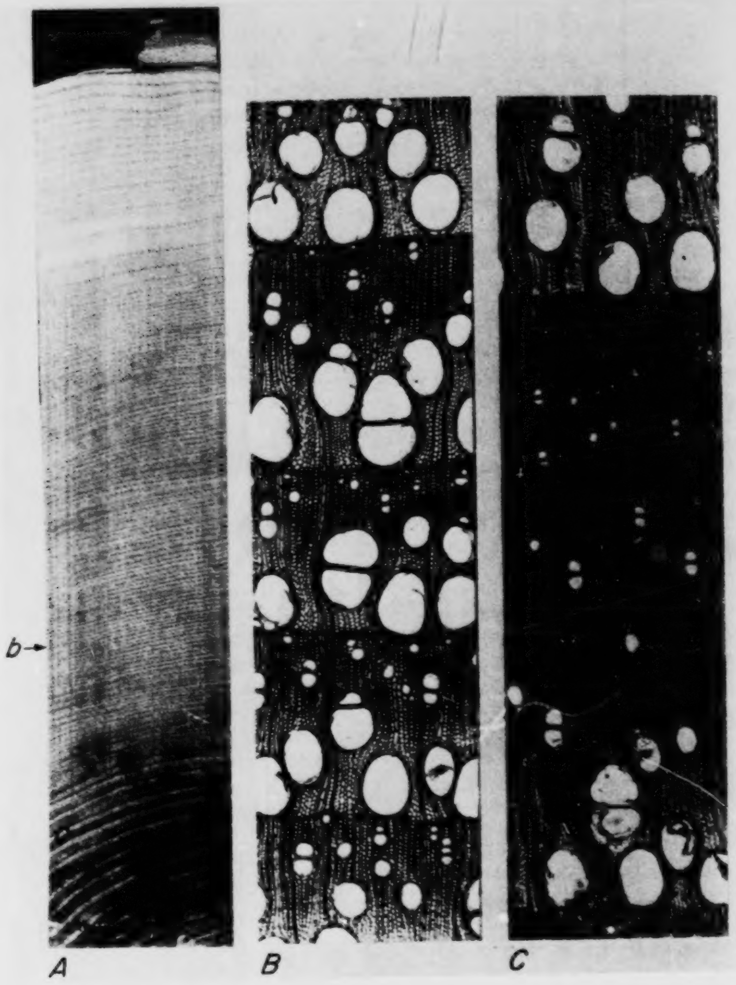

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Figure 7-6.—Changes in rate of diameter growth and structure of annual rings in white ash. (A) Cross section showing transition from wood of rapid growth and high specific gravity near center of tree (a to c), to wood of slow growth and low specific gravity (b). (B and C) Photomicrographs illustrating numerous vessels distributed across the narrow growth rings in slow-grown wood (B) and the nearly vessel-free wide rings typical of fast-grown wood (C). The specific gravity of the wood of B is only 0.48, while that of C is 0.65 based on ovendry weight and volume when green. (Photo from Paul 1963.)

Pillow (1950) concluded that woodsmen can select, by external characteristics, vigorous trees that will produce tough ash of adequate specific gravity. Such trees have relatively large, upward-tapering, and generally well-shaped crowns without large dead branches. Crowding by neighboring trees causes misshapen crowns, slows diameter growth, and reduces quality. The bark of ash also offers clues to quality. Vigorous trees producing desirable wood have tight bark, with low ridges and shallow depressions, showing light-colored streaks of inner bark.

ELM, AMERICAN

Ten 6-inch American elm trees from southern pine sites sampled Southwide (table 3-1) had average specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.536	0.020
Branchwood	.526	.035
Tree wood	.535	.020

The specific gravity for 6-inch trees shown above (0.54) is substantially higher than the value (0.46) for larger American elms shown in Table 7-6.

ELM, WINGED

Ten 6-inch winged elm trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.623	0.030
Branchwood	.610	.031
Tree wood	.622	.029

Stemwood specific gravity of these small trees (0.62) is somewhat higher than that of wood from larger merchantable trees (table 7-6) sampled throughout the United States range of the species (0.60).

In a sample of 80- to 230-year-old winged elm trees from Arkansas, Louisiana, and Texas, trees from Arkansas had highest specific gravity (0.60), and those from Louisiana had the lowest (0.56); average specific gravity was inversely correlated with average rings per inch (table 7-11). From this study Baudendistal and Paul (1944) concluded that winged elm—and cedar elm (*Ulmus crassifolia* Nutt.) as well—could be substituted for rock elm (*Ulmus thomasi* Sarg.) in many uses where strength and toughness are primary considerations.

TABLE 7-11.—*Specific gravity of stemwood at various heights in 5 winged elms from each of three southern stands* (Baudendistel and Paul 1944)

Location and sample height (feet)	Range in tree ages	Range in dbh	Average rings per inch of radius	Specific gravity[1]		
				Samples	Range	Average
	Years	*Inches*	*Number*	*Number*		
Ashley County, Arkansas	80-230	18-25				
0-4			9	26	0.56-0.72	0.64
5-8			13	26	.57-.71	.62
9-20			15	40	.53-.70	.59
20+			17	31	.51-.62	.56
Average, 0-20+			14			.60
Montgomery County, Texas	107-152	14-23				
0-4			16	24	0.50-0.67	0.59
5-8			17	22	.53-.68	.60
9-20			17	30	.46-.66	.58
20+			17	16	.51-.64	.58
Average, 0-20+			17			.59
Morehouse Parish, Louisiana	154-218	14-20				
0-4			28	21	0.52-0.66	0.60
5-8			25	19	.50-.62	.57
9-20			27	35	.47-.61	.56
20+			24	26	.44-.58	.53
Average, 0-20+			26			.56

[1] Unextracted, ovendry weight and green volume basis.

HACKBERRY

Ten 6-inch hackberry and sugarberry trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.525	0.047
Branchwood	.551	.048
Tree wood	.527	.047

Stemwood specific gravity of these small pine-site trees (0.53) is somewhat higher than that reported (table 7-6) for larger merchantable trees on all sites (0.49).

Six 45-year-old sugarberrry trees cut near Stoneville, Miss., showed little correlation between annual ring width and specific gravity (Taylor 1971).

HICKORY, TRUE

Ten 6-inch true hickory trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.643	0.075
Branchwood	.607	.061
Tree wood	.641	.072

Stemwood specific gravity from these 6-inch hickories averaged about the same (0.64) as that of larger mockernut, pignut, and shagbark hickories (table 7-6) sampled throughout their ranges (0.64, 0.66, and 0.64).

Twenty-four understory hickories averaging 3.0 inches in dbh (12 from the mountains of North Carolina and 12 from the Piedmont of Georgia) had higher stemwood specific gravity but about the same branchwood specific gravity as the 6-inch pine-site hickories, as follows (Phillips 1977):

Tree portion	Mountains (North Carolina)	Piedmont (Georgia)	24-Tree average
Stemwood	0.631	0.673	0.652
Branchwood	.578	.641	.609
Tree wood	.624	.665	.645

Piedmont trees were denser (0.665) than those from the mountains (0.624).

Taylor (1977a) found little geographic variation in the specific gravity of increment cores taken at breast height from Mid-South mockernut and shagbark hickory trees averaging about 11 inches in dbh and ranging from 51 to 126 years old. Mockernut hickory from Louisiana's Kisatchie National Forest had higher specific gravity than that from the other Mid-South locations, however. Each value in the following tabulation is the average for 10 trees; an asterisk indicates a correlation or difference significant at the 5-percent level:

Species and location	Specific gravity of mature wood from breast-height cores	Standard error of mean	Coefficient of correlation between annual ring width and specific gravity of mature wood
Mockernut hickory			
Central Louisiana..................	0.71*	0.009	0.42
North Mississippi..................	.68	.015	.15
North Alabama	.65	.008	.68*
Central Arkansas	.64	.004	.54
South Mississippi..................	.64	.004	.31
South Alabama	.64	.010	.74*
Shagbark hickory			
North Mississippi..................	0.65	0.008	0.41
North Alabama	.65	.012	.01
Central Arkansas	.64	.004	.47

Only in the two Alabama locations were widths of annual rings in mature wood (rings 21 to bark) significantly correlated with the specific gravity of this wood, and then only for mockernut hickory; at these two locations fast diameter growth yielded dense wood. In juvenile wood (rings 1 to 10), cores from central Arkansas and from North Alabama showed significant positive correlations (0.76 and 0.67) between ring width of mockernut hickory and its specific gravity.

The relationship of diameter growth rate to specific gravity is evidently complex. Paul (1926) concluded that hickory of low specific gravity follows interruption of normal growth. Thus hickories with slow initial growth produce heavy wood while growth is uniform or increasing, but specific gravity decreases with the first noticeable decline in growth rate (fig. 7-7). Paul (1963) again noted that a sustained or accelerated diameter growth in hickory produces wood of uniform specific gravity, while retarded growth from crowding or from site deterioration decreases specific gravity.

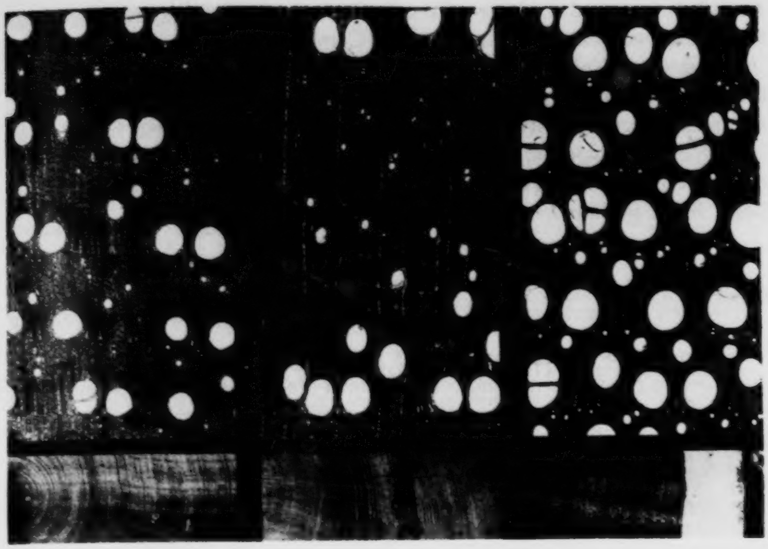

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Figure 7-7.—Relation of wood density to growth rate and radial position in old-growth hickory trees. Cross sections and corresponding photomicrographs show, left to right, narrow growth rings near pith—wood of high density; then wider growth rings—wood of high density; and subsequent narrow growth rings—wood of low density. (Photo from Paul 1963.)

MAPLE, RED

Ten 6-inch red maple trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variation as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.496	0.014
Branchwood	.507	.013
Tree wood	.495	.015

Average stemwood specific gravity for these 6-inch trees is about the same as that of larger merchantable red maple (table 7-6) sampled throughout the species range in the United States (0.49).

In Georgia and North Carolina, small understory red maple trees averaging 3 inches in diameter had higher stemwood specific gravity than the 6-inch trees of the Southwide sample; branchwood specific gravity was about the same, as follows (Phillips 1977):

Tree portion	Mountains (North Carolina)	Piedmont (Georgia)	24-Tree average
Stemwood	0.513	0.518	0.515
Branchwood	.504	.512	.508
Tree wood	.511	.516	.513

As with hickory, red maple trees from the Piedmont were slightly denser (0.516) than those from the mountains of North Carolina (0.511).

Kellison and Zobel's (1971) sample of 71 red maples collected from the Piedmont region and the Atlantic and Gulf Coastal Plains averaged 0.46 in stemwood specific gravity with tree averages for stemwood ranging from 0.40 to 0.58. Stemwood specific gravities were greatest on upland slopes in the Piedmont (0.56), and least in Coastal-Plain forest types of Louisiana's Red River and Black River Bottoms.

OAK

Within-species variation in the oaks growing on southern pine sites will be discussed in the following subsections which are arranged in alphabetical sequence by common name. By way of introduction, a few generalizations seem appropriate.

In nearly all the oak trees—both red and white—investigated by Paul (1963) in 10 locations in the Appalachian region of Kentucky, West Virginia, and North and South Carolina, ring width and specific gravity decreased progressively from the pith outward. In most species, however, some trees showed contrasting regressions of specific gravity and rings per inch when growth patterns were unlike. He concluded that ring width did not control oak wood specific gravity, since wood with narrow rings near the center of trees was of average or higher specific gravity, but when ring width, declined progressively toward the bark, specific gravity decreased concurrently.

Among three white oak and nine red oak species from the southeastern United States, Paul (1942) found that upland red oaks had decidedly more vessel volume (i.e., were more porous) than those from lowland areas. Within an oak species he found considerable variation in vessel volume from stand to stand; lower vessel volume appeared associated with the more vigorous trees in all species except chestnut oak. In trees of the red oak group, wood just above the stump had the least vessel volume with a maximum at 15 or 20 feet; from that point upward, there was tendency toward decrease in vessel volume in some species. The effects of these within-tree variations in vessel volume on specific gravity are illustrated in section 7-6.

Since ray density in oaks is greater than that of total wood tissue, ray percentage may account for some differences in average tree specific gravity; the influence of ray tissue percentage is probably greater in red oaks than in white, as follows (Taylor 1969):

Species group	Total tissue specific gravity	Ray specific gravity
Red oaks	0.61	0.69
White oaks	.63	.64

OAK, BLACK

Ten 6-inch black oak trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.620	0.022
Branchwood	.648	.030
Tree wood	.622	.021

These 6-inch trees had stemwood of somewhat higher specific gravity (0.62) than larger merchantable trees sampled (table 7-6) from throughout the species range (0.56)

Fifteen black oak trees of intermediate size (10.2-11.6 inches in dbh and ranging from 63 to 88 years old) sampled in North and South Carolina had specific gravity averaging 0.60, an intermediate value.

OAK, BLACKJACK

Ten 6-inch blackjack oak trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.638	0.024
Branchwood	.706	.039
Tree wood	.645	.027

No other data on within-species variation of the specific gravity of blackjack oak are available.

OAK, CHERRYBARK

Ten 6-inch cherrybark oak trees from southern pine sites Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.623	0.036
Branchwood	.640	.024
Tree wood	.624	.033

These 6-inch trees had stemwood of about the same specific gravity (0.62) as larger merchantable trees sampled (table 7-6) from throughout the species range (0.61)

In a study of ten trees from each of three natural stands of cherrybark oak 40 to 60 years old, in each of two areas (bottomland in western Tennessee and Brown-Loam Hills of west-central Mississippi), specific gravity did not vary significantly between areas. Specific gravity of breast-height samples within the span of 10 to 50 rings from the pith ranged from 0.533 to 0.693, and averaged 0.602. Specific gravity was positively correlated with ring width; variance components were greatest for trees within stands, next largest for samples within trees, and smallest for stands within areas (Farmer and Nance 1969).

OAK, CHESTNUT

Eleven understory chestnut oak trees averaging 3 inches in dbh sampled in the mountains of North Carolina had specific gravity as follows (Phillips 1977):

Tree portion	Specific gravity
Stemwood	0.630
Branchwood	.590
Tree wood	.625

The stemwood specific gravity of these small tress (0.63) is considerably greater than the species average (table 7-6) for stemwood from larger merchantable chestnut oak trees (0.57).

Date for 6-inch trees growing on southern pine sites are not available.

OAK, LAUREL

Ten 6-inch laurel oak trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.582	0.030
Branchwood	.624	.034
Tree wood	.586	.031

Stemwood of these 6-inch trees had higher specific gravity (0.58) than the species average (table 7-6) for stemwood from larger merchantable laurel oak trees (0.56). No other data are available on within-species variability of laurel oak.

OAK, NORTHERN RED

Ten 6-inch northern red oak trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.605	0.056
Branchwood	.597	.034
Tree wood	.605	.034

Stemwood of these 6-inch trees had higher specific gravity (0.60) than the species average (table 7-6) for stemwood from larger merchantable northern red oak trees sampled throughout their range in the United States (0.56).

Five northern red oaks of intermediate size (62 to 70 years old and 13.5 to 16.5 inches in diameter), grown at 3,250 feet in North Carolina on black alluvial soil had average stemwood specific gravity of 0.57—an intermediate value (Paul 1963).

Davis (1973) found that northern red oak trees grown on sandstone derived soils had significantly higher stemwood specific gravity than those grown on limestone derived soils. Murphy et al. (1973) observed that 5 years of irrigation of northern red oaks with sewage effluent significantly increased specific gravity of their stemwood.

Maeglin[1], in a study of breast-height increment cores from 30 North Carolina northern red oaks, observed that specific gravity in annual rings 38-47 had a significant positive correlation with percentage of fibers (R = 0.394).

OAK, POST

Ten 6-inch post oak trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.659	0.038
Branchwood	.656	.044
Tree wood	.658	.036

Stemwood of these 6-inch trees had 10 percent higher specific gravity (0.66) than the species average (table 7-6) for stemwood of larger merchantable post oak trees (0.60).

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[1] Personal communication from R. R. Maeglin, U.S. Forest Products Laboratory, Madison, Wis., Dec. 9, 1977.

Taylor (1977a) found little geographic variation in specific gravity at breast height among Mid-South post oaks averaging about 10.5 inches in dbh and ranging from 55 to 71 years old. Each value in the following tabulation is the average for 10 trees; an asterisk indicates a correlation significant at the 5-percent level:

Location	Specific gravity of mature wood from breast-height cores	Standard error of mean	Coefficient of correlation between annual ring width and specific gravity of mature wood
South Mississippi.........	0.64	0.008	0.15
South Alabama	.64	.012	.45
Central Louisiana.........	.63	.010	−.11
Central Arkansas	.63	.010	.64*
North Mississippi.........	.63	.011	.36
North Alabama	.61	.010	.31

Only the Central Arkansas area were widths of annual rings in mature wood (rings 21 to bark) significantly correlated with specific gravity of the wood; in this sampling area fast diameter growth yielded dense wood. Specific gravity of juvenile wood (rings 1-10) was not significantly correlated with ring width in any of the six areas.

OAK, SCARLET

Ten 6-inch scarlet oak trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood...	0.622	0.030
Branchwood	.643	.024
Tree wood...	.623	.029

Stemwood of these 6-inch trees had higher specific gravity (0.62) than the species average (table 7-6) for stemwood from larger merchantable trees (0.60).

Stemwood of intermediate-size scarlet oaks from the Carolinas—five sampled from each state—had even lower specific gravity, as follows (Paul 1963):

Statistic	North Carolina (McDowell County)	South Carolina (McCormack County)
Tree age (years)..................	41-67	71-99
Dbh (inches)	11.0-17.5	13.4-19.3
Soil type..........................	Light-brown clay	Red clay loam
Elevation (feet)	1,400	500
Specific gravity	0.575	0.587
Between-tree standard deviation.....	0.021	0.033

OAK, SHUMARD

Ten 6-inch Shumard oak trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.625	0.040
Branchwood	.643	.021
Tree wood	.627	.038

No other data are available for Shumard oak.

OAK, SOUTHERN RED

Ten 6-inch southern red oak trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.609	0.020
Branchwood	.621	.026
Tree wood	.610	.024

Stemwood of these 6-inch trees had substantially higher specific gravity (0.61) than the species average (table 7-6) for stemwood from larger merchantable trees (0.52).

Thirteen small (3-inch dbh average) southern red oak trees sampled from understories in the Piedmont of Georgia had about the same specific gravity as the 6-inch trees mentioned above, as follows (Phillips 1977):

Tree portion	Specific gravity
Stemwood	0.592
Branchwood	.617
Tree wood	.595

Five southern red oaks of intermediate size (10.2- to 19.5-inch dbh and 35 to 128 years of age) sampled at each of four locations in North and South Carolina at elevations from 500 to 2,200 feet averaged 0.570 in specific gravity of stemwood (location averages ranged from 0.557 to 0.587); between-tree standard deviation at the four locations sampled was about 0.031 (Paul 1963).

Taylor (1977a) found no significant geographic variation in breast-height specific gravity of Mid-South southern red oak trees averaging about 11.0 inches in dbh and ranging from 39 to 52 years old. Each value in the following tabulation is the average for 10 trees:

Location	Specifc gravity of mature wood from breast-height cores	Standard error of mean
South Alabama	0.61	0.008
Central Louisiana	.59	.010
North Alabama	.59	.006
North Mississippi	.59	.007
Central Arkansas	.58	.014
South Mississippi	.57	.007

Breast-height specific gravity of these 60 trees was not significantly correlated with width of annual rings. In a second 12-tree sample of southern red oak from these same locations, however, entire stemwood specific gravity was inversely correlated with ring width, i.e., fast growth rate was associated with low specific gravity (Taylor 1978).

OAK, WATER

Ten 6-inch water oak trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.587	0.034
Branchwood	.604	.026
Tree wood	.588	.033

Stemwood of these 6-inch trees had slightly higher specific gravity (0.59) than the species average (table 7-6) for stemwood from larger merchantable water oak trees (0.56).

Five 12.2- to 12.7-inch water oaks 30 to 40 years old sampled from red loam sites at an elevation of 500 feet in McCormack County, South Carolina had average stemwood specific gravity of 0.595 with between-tree standard deviation of 0.024 (Paul 1963).

Geographic variation of breast-height specific gravity in Mid-South water oaks averaging about 10.6 inches in dbh and from 38 to 50 years old was not significant (Taylor 1977a). Each value in the following tabulation is the average for 10 trees:

Location	Specifc gravity of mature wood from breast-height cores	Standard error of mean
North Mississippi	0.61	0.007
South Mississippi	.60	.010
Central Louisiana	.59	.011
Central Arkansas	.58	.008
South Alabama	.57	.010

Breast-height specific gravity of these 50 trees was not significantly correlated with width of annual rings. In a second 12-tree sample of water oak from these same locations, however, entire stemwood specific gravity was inversely correlated with ring width, i.e., fast growth rate was associated with low specific gravity (Taylor 1968).

OAK, WHITE

Ten 6-inch white oak trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.665	0.053
Branchwood	.637	.039
Tree wood	.664	.051

Stemwood of these 6-inch trees had substantially higher specific gravity (0.67) than the species average (table 7-6) for stemwood from larger merchantable white oak trees sampled throughout the United States range (0.60).

In Georgia and North Carolina, small understory white oak trees averaging 3 inches dbh also had lower stemwood and branchwood specific gravity than the 6-inch pine-site trees, as follows (Phillips 1977):

Tree portion	Mountains (North Carolina)	Piedmont (Georgia)	24-Tree average
Stemwood	0.624	0.608	0.616
Branchwood	.588	.612	.600
Tree wood	.619	.608	.613

Twenty-five white oaks of intermediate size (8.5 to 19.0 inches dbh and 54 to 125 years old) sampled in five locations in North and South Carolina at elevations from 500 to 2,800 feet had little variation in stemwood specific gravity attributable to geographic location; the range in location averages was from 0.610 to 0.633 with grand mean of 0.623. Between-tree standard deviation was about 0.032 (Paul 1963).

SWEETBAY

Ten 6-inch sweetbay trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.437	0.037
Branchwood	.423	.039
Tree wood	.436	.037

Stemwood of these 6-inch trees (0.44) had about the same specific gravity as the species average (table 7-6) for stemwood from larger merchantable sweetbay trees (0.45). Jett and Zobel (1975) reported specific gravity of mature stemwood of sweetbay as 0.43.

SWEETGUM

Ten 6-inch sweetgum trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.453	0.017
Branchwood	.451	.028
Tree wood	.453	.017

Stemwood of these 6-inch trees had about the same specific gravity (0.45) as the species average (table 7-6) for stemwood of larger merchantable sweetgum trees (0.46).

Stemwood of 1-year-old seedlings had specific gravity in the range from 0.34 to 0.47 (Roberds 1965). Stemwood of 2-year-old sweetgum had specific gravity of 0.45 and moisture content of 134 percent of dry weight; stemwood from 6-year-old trees also had a specific gravity of 0.45 (range 0.42 to 0.48) with moisture content of 137 percent of dry weight (range 123 to 147 percent) (Jett and Zobel 1975).

In the Piedmont Region of Georgia, twelve small understory sweetgum trees averaging 3 inches in dbh had the same stemwood gravity as the 6-inch pine site sweetgum as follows (Phillips 1977):

Tree portion	Specific gravity
Stemwood	0.448
Branchwood	.458
Tree wood	.449

Among 225 sweetgum trees sampled from 21 stands in Mississippi, Florida, Georgia, North Carolina, South Carolina and Virginia, the sample tree with the highest specific gravity in each stand averaged 0.04 greater than the stand average; this represents a difference of 2.53 pounds per cubic foot of wood substance. Specific gravity was not consistently related to growth rate (Webb 1965). In a study of 87 five-tree plots of sweetgum in Alabama, Hunter and Goggans (1968) also found growth rate not correlated with stemwood specific gravity.

Kellison and Zobel's (1971) sample of 76 sweetgum trees from the Piedmont and Atlantic and Gulf Coastal Plains had mean stemwood specific gravity of 0.46 (range 0.41 to 0.53) and moisture content of 121 percent of dry weight (range 98-145 percent). Highest specific gravity was found in trees from a Coastal Plain muck swamp (0.51); specific gravity of stemwood from upland slopes in the Piedmont and Coastal Plain ridges averaged 0.47

Breast-height samples of annual rings 11 through 20 taken from 10 sweetgum trees growing on dry upland sites and another 10 from nearby bottomland sites in each of the four widely separated geographic areas, showed that upland sweetgum stemwood has higher specific gravity than bottomland sweetgum (fig. 7-8); geographic differences in specific gravity were generally not significant, however (Webb 1964).

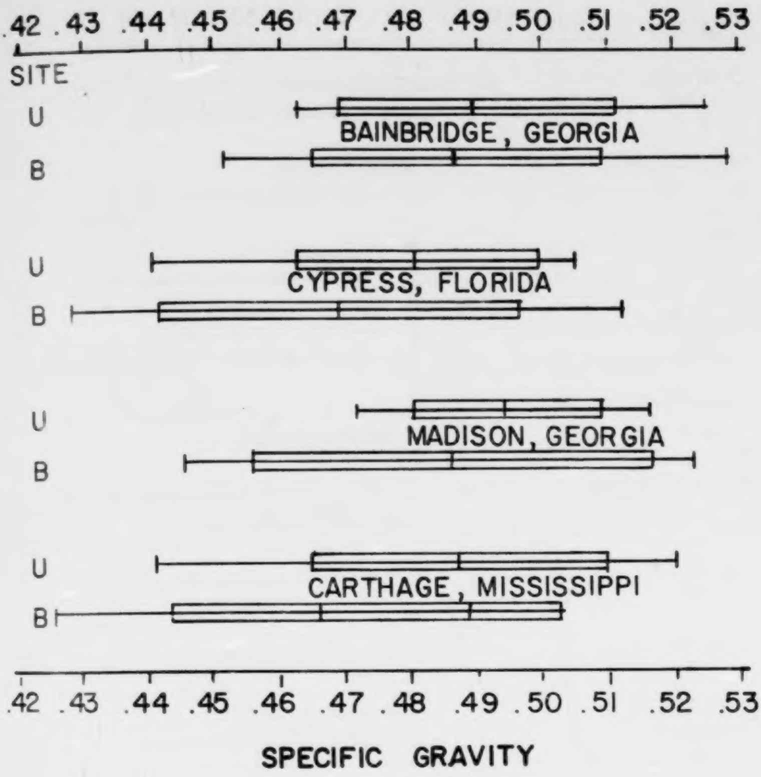

Figure 7-8.—Variation in specific gravity (unextracted ovendry weight and green volume basis) of sweetgum breast-height increment cores (rings 11 through 20) on upland (U) and bottom land (B) sites at four locations. Each bar diagram contains data describing 10 trees, and indicates the most- and least-dense trees at each site; the box includes one standard deviation on either side of the site mean. (Drawing after Webb 1964.)

In a separate study (rings 11 through 20) of 10 trees (or more) sampled from each of two stands in each of 11 areas from Florida to Virginia, variation in breast-height specific gravity with geographic location was not significant (figs. 7-9 and 7-10).

Sweetgum trees sampled from east Texas through all the southernmost tier of States to North Carolina (except Florida) showed no significant relationship between specific gravity at breast height and geographic location (Johnson and McElwee 1967). Winstead (1972) concluded, on the basis of seedlings from sources in Mexico as well as the United States, that specific gravity of sweetgum seedlings decreased with decrease in latitude of seed origin.

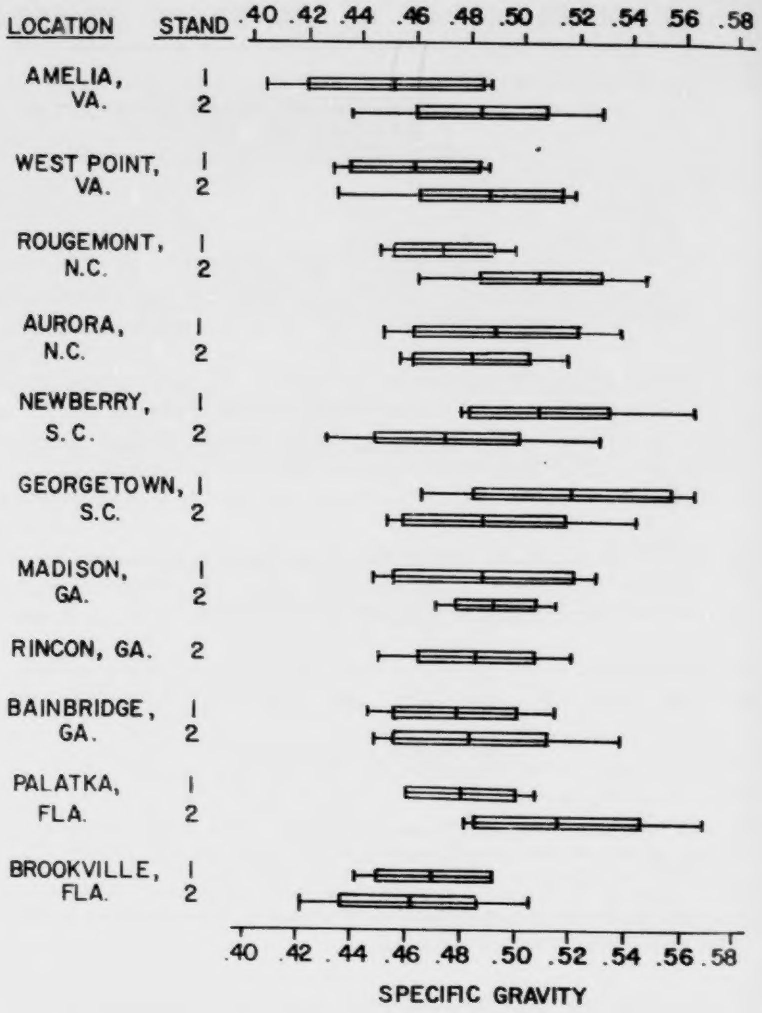

Figure 7-9.—Variation in breast-height specific gravity (unextracted ovendry weight and green volume basis) within stands of sweetgum. Stands represented at top of figure are northernmost, those at the bottom southernmost. Range of the 10-tree minimum sample is indicated for each stand; the box encloses one standard deviation on either side of the standard mean. (Drawing after Webb 1964.)

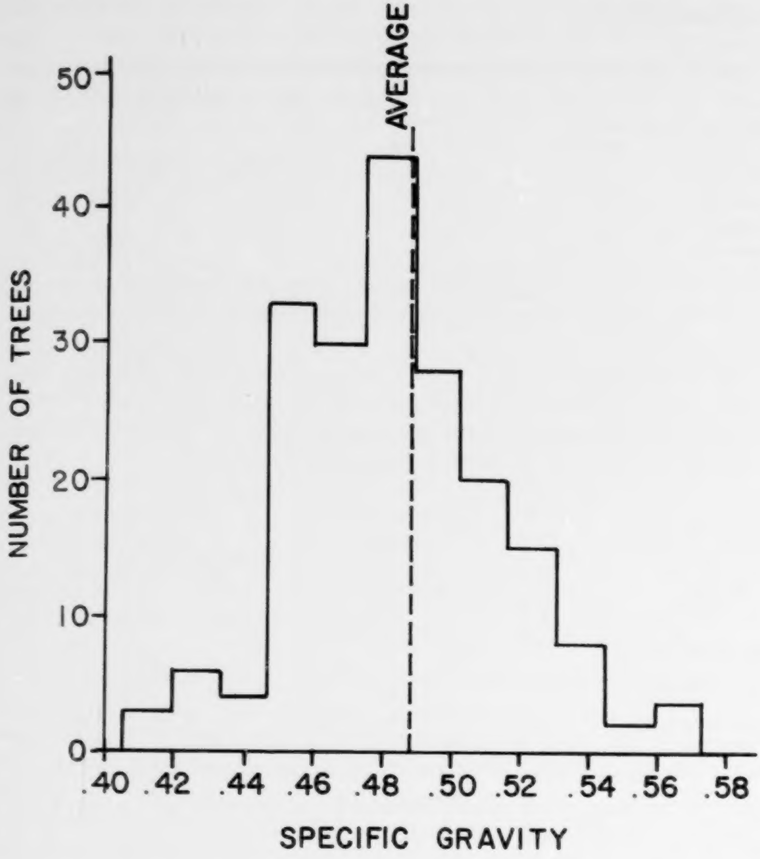

Figure 7-10.—Frequencies of sweetgum specific gravities in rings 11 to 20 at breast height (unextracted ovendry weight and green volume basis) of 195 trees from stands described in figure 7-9. (Drawing after Webb 1964.)

TUPELO, BLACK

Ten 6-inch black tupelo trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.500	0.041
Branchwood	.487	.050
Tree wood	.500	.040

These 6-inch pine-site trees had stemwood of somewhat higher specific gravity (0.50) than larger merchantable trees (table 7-6) sampled throughout the species' range (0.46).

Taylor (1977a) determined average breast-height specific gravity of Mid-South black tupelo trees 37 to 86 years old averaging about 10.9 inches in diameter; the differences between stands were not statistically significant. Each value in the following tabulation is the average for 10 trees:

Location	Specific gravity of mature wood from breast-height cores	Standard error of mean	Coefficient of correlation between annual ring width and specific gravity of mature wood
South Alabama	0.56	0.007	−.29
North Alabama	.54	.006	.63
Central Louisiana	.54	.015	−.15
South Mississippi	.53	.010	−.31
Central Arkansas	.52	.010	.00
North Mississippi	.50	.013	.03

Annual ring widths were not significantly correlated with specific gravity in either mature or juvenile wood of these black tupelo trees.

YELLOW-POPLAR

Ten 6-inch yellow-poplar trees from southern pine sites sampled Southwide (table 3-1) had average wood specific gravity and between-tree variability as follows (table 7-7):

Tree portion	Average	Standard deviation
Stemwood	0.395	0.032
Branchwood	.406	.036
Tree wood	.395	.032

These 6-inch pine-site trees had the same stemwood specific gravity as that for stemwood of merchantable trees (table 7-6) sampled throughout the species range (0.40).

Small understory yellow-poplar trees from Georgia and North Carolina (averaging 3 inches dbh) had lower stemwood specific gravity than the 6-inch pine-site trees sampled Southwide; branchwood specific gravity was about the same, as follows (Phillips 1977):

Tree portion	Mountains (North Carolina)	Piedmont (Georgia)	24-Tree average
Stemwood	0.367	0.388	0.377
Branchwood	.406	.400	.403
Tree wood	.371	.390	.380

Stemwood of understory yellow-poplar from the Piedmont was slightly more dense than that from the mountains of North Carolina.

Mid-South samples of yellow-poplar in an intermediate diameter class (11.6 inches average dbh, ages 31 to 41 years) had breast-height specific gravity of 0.45, as follows (Taylor 1977a); each tabulated value is the average of 10 trees:

Location	Specific gravity of mature wood from breast-height cores	Standard error of mean	Coefficient of correlation between annual ring width and specific gravity of mature wood
North Mississippi	0.45	0.010	−0.04
North Alabama	.45	.010	.01
South Alabama	.45	.014	−.57
South Mississippi	.44	.008	−.07

Clark et al. (1974) found that, in a stand of yellow-poplar ranging from 12 to 26 inches dbh, wood specific gravity was not correlated with tree diameter. In their study, 47 yellow-poplar trees from a mountain-cove, natural, mature, uneven-aged (56 to 99 years) stand in Western North Carolina were selected to include 5 or 6 trees in each even-inch diameter class from 12 to 26 inches and two trees in the 28-inch class. Sample trees averaged 19.3 inches dbh and 69 feet to an 8-inch top. Wood specific gravity averaged 0.412 in the sawlog portions of the stems, 0.428 in the pulpwood portions, and 0.436 in the topwood. Weighted wood specific gravity did not vary significantly with tree size except in the 28-inch trees, whose specific gravity was 10 percent higher than the study average (Clark et al. 1974).

Thorbjornsen (1961) found that specific gravities of individual trees are normally distributed and that considerable differences exist among trees sampled from small plots. He observed no significant differences between stands, whereas Sluder (1972) concluded that specific gravity is inversely related to site index. A 25-tree sample of 18-year-old plantation-grown yellow-poplar from Pope County, Illinois showed no correlation between site index and stemwood specific gravity (Gilmore 1971). Davis (1973) found that breast-height specific gravity of yellow-poplar wood grown on sandstone derived soils was the same as that grown on limestone-derived soils.

Neither fertilization nor irrigation have been found to affect specific gravity of yellow-poplar stemwood (Thor and Core 1972).

Some of the density variation in yellow-poplar is attributable to percentage of parenchyma cells, which have thick cell walls and stored cell contents (Barefoot 1963). Taylor (1969) found that the average specific gravity of rays in yellow-poplar (0.58) was considerably higher than the specific gravity (0.41) of the sample blocks containing the rays.

The relationship between annual ring width and specific gravity of yellow-poplar is complex. Efforts to find a significant correlation between ring width in juvenile or mature wood and wood specific gravity have in some experiments been unsuccessful (Taylor 1965, 1968, 1977), while in others (Erickson 1949, Wooten et al. 1973) fast growth rate has been associated with high specific gravity. It seems likely that in yellow-poplar very fast-grown wood (3 to 7 rings per inch) near the pith, and very slow-grown wood in outer rings both have lower than average specific gravity (Luxford and Wood 1953).

Paul (1962) concluded that yellow-poplar wood of the lowest specific gravity is usually the portion of old-growth trees havng extremely narrow annual rings. He reported highest specific gravity in young trees maintaining wide to medium ring width. In stands originating in the open, very wide rings near the pith tend to have below-average specific gravity. This concept is illustrated by a tabulation of stemwood specific gravity for mountain old-growth and second-growth yellow-poplar, as follows (Paul 1962):

Rings per inch	Old-growth	Second-growth
Less than 5	0.39	0.40
6 to 10	.40	.43
11 to 15	.41	.44
16 to 20	.38	.44
21 and over	.37	.43

Paul concluded that narrow-ringed yellow-poplar wood contains a high proportion of large thin-walled cells; such wood is lighter and softer than wide-ringed wood. (fig. 7-11).

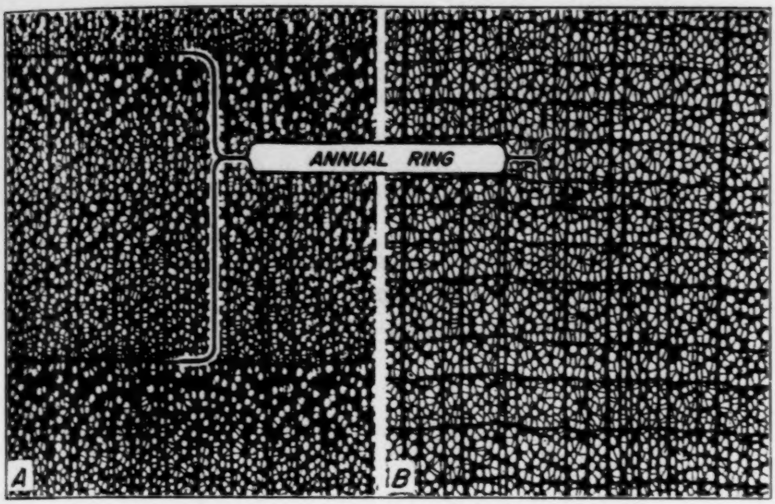

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Figure 7-11.—Structure of wood produced during periods of rapid and of slow growth in an old-growth yellow-poplar tree. Wood at left has a specific gravity of 0.41, and was produced during the early life of the tree, while it enjoyed sufficient growing space; wood at right was produced during a time when the trees of the stand were keenly competing for growing space and moisture; it has a specific gravity of 0.31. (Photo from Paul and Norton 1936.)

From 10 yellow-poplar trees sampled from each of 50 stands in Virginia, North Carolina, and Georgia, Sluder (1972) found that breast-height stand specific gravity was normally distributed from 0.32 to 0.55 with stand average of 0.41. He concluded that specific gravity in these trees decreased with increasing elevation, more northerly latitudes, and increasing site index.

Kellison (1967) found significant geographic variation in a North Carolina sample of 108 30- to 50-year-old yellow-poplar trees from nine stands in each of the state's physiographic areas—Coastal Plain, Piedmont, and Mountains. The regional average for the Piedmont (0.43 at breast-height) was greater than that for either the Coastal Plain (0.42), or the Mountain Region (0.41). These regional variation patterns are similar to those observed by Taylor (1965) and Barefoot (1958), who also found that Piedmont yellow-poplar had wood of greatest density (fig. 7-12).

In Mississippi and Alabama, however, Taylor (1977a) found no geographic variation in specific gravity.

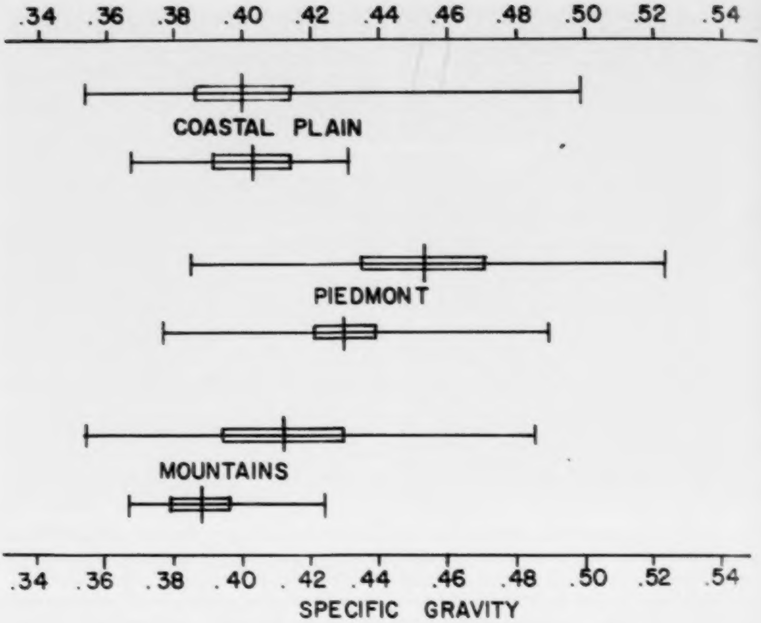

Figure 7-12.—Yellow-poplar specific gravity (based on unextracted ovendry weight and green volume of rings 21 through 25 in breast-height increment cores) in six stands on an east-west transect across North Carolina. The length of each line represents the extremes of measurements for each stand; the middle crossbar denotes the mean, and the rectangle encloses a length two times the standard error of the mean to each side of the mean. (Drawing after Taylor 1965.)

7-6 WITHIN-TREE VARIATION

Specific gravity in stemwood of hardwoods may vary across each annual ring, with radial position in the stem, and with height above the ground. In the following discussions of these variations, as elsewhere in this book, specific gravity values are based on unextracted ovendry weight and green volume, unless otherwise noted.

Variation of specific gravity across annual rings of ring-porous hardwoods is largely attributable to distribution of vessels (figs. 7-6 and 7-7). Benic (1955) observed that the ratio of latewood specific gravity to that of earlywood was 1.25 for *Fraxinus excelsior* L.; Muller-Stoll (1948) reported somewhat greater ratios, as follows:

Species	Specific gravity		Ratio
	Earlywood	Latewood	
Fraxinus excelsior L.	.385-.506	.721-.803	1.55-2.03
Quercus spp.	.317-.454	.888-.930	1.96-2.80

Data specific to hardwoods on pine sites is scarce or lacking.

Kollman and Côté (1968, p. 177) related average specific gravity of ash wood (*Fraxinus excelsior* L.) to latewood percentage, as follows:

Latewood percentage	Specific gravity (conditions unspecified)
40	0.53
50	.61
60	.66
70	.68
80	.69

Bethel (1943) found that specific gravity of chestnut oak had linear positive correlation with latewood content (see equation 7-6).

Within earlywood and latewood there are also variations in specific gravity according to tissue type. For example, Morschauser (1954) observed that ray tissue in northern red oak had 1.5 times the density of surrounding fibrous tissue.

Statistical analysis of data from table 7-7 permit a few conclusions about the specific gravities of stemwood and branchwood. (Bark variations and comparisons with wood specific gravity will be discussed in chapter 13.) In all but two species differences between stemwood and branchwood specific gravities were non-significant; in laurel oak and blackjack oak branchwood specific gravity exceeded that of stemwood, by 0.042 and 0.068, respectively. In Manwiller's (1979) study, stemwood properties dominated tree values; 82 percent of above-stump green weight—all species averaged—was attributable to stemwood.

The following discussions of specific gravity variations with radial position and height in tree are arranged alphabetically by species common name.

ASH

In breast-height increment cores from 17 white ash trees sampled from a 4-acre plot in Hancock County, Georgia—a Piedmont, bottom land, alluvial site—McElwee et al. (1970) found no difference in specific gravities between annual rings 1-10 and 11 plus. Other workers, however, have observed substantial variation in specific gravity of ash with radial position in the stem (figs. 7-5 and 7-6). From a broad series of studies Paul (1960, 1963) concluded that in white ash, wood of uniform high specific gravity results when rapid diameter growth is maintained, but with the first noticeable decrease in growth rate, wood specific gravity in the affected annual rings also decreases; resumption of rapid growth again results in production of high-density wood.

Variations of ash wood specific gravity with height in tree appear to follow complex patterns. Some trees show little variation. For example, both branchwood and stemwood of 6-inch green ash trees growing on pine sites (table 7-7) had gravity of 0.56, although topmost stemwood averaged about 0.60; white ash branchwood was only slightly less dense (0.56) than the stemwood of white ash (0.58) which showed little variation with height (fig. 7-13). Similarly, in a study that sampled green ash trees 20 to 60 years old grown throughout the Piedmont and Atlantic and Gulf Coastal Plain, Kellison and Zobel (1971) found practically no difference in specific gravity or moisture content from base to top within a tree; in their study, breast-height samples of green ash (0.54 specific gravity) yielded a good estimate of entire stemwood specific gravity (0.55).

Paul (1963), however, cautions that white and green ash from upland locations have bottom sections that are denser than upper portions; this pattern contrasts with ash subject to periodic inundation where wood near the stump proved lightest. Pillow's (1939, 1950) data for green ash (fig. 7-3), show three distinctly different patterns of variation in specific gravity with height in tree, depending on site and stand conditions.

ELM

Branchwood of 6-inch trees of American and winged elm grown on pine sites is slightly lower in specific gravity (about 0.01 less) than that of stemwood (table 7-7). This is consistent with observations (table 7-11) that butt sections of winged elm from Arkansas, Texas, and Louisiana had higher stemwood specific gravity (0.61) than stem sections at 20 feet and higher above ground (0.56). Data on 6-inch winged elm and American elm from southern pine sites also indicate that elm stemwood has highest specific gravity near ground level (fig. 7-13).

No data specific to radial variation in elm are available, but wood of uniform high specific gravity probably results when radial growth rate is maintained or increased; decreased radial growth probably yields wood of lower specific gravity.

HACKBERRY

Six-inch hackberry and sugarberry trees sampled Southwide from southern pine sites (table 7-7) had higher specific gravity in branchwood (0.55) than in stemwood (0.52); uppermost stemwood (38-foot level) had highest specific gravity (fig. 7-13). In Taylor's (1971) sample of six 45-year-old, 73-foot-tall, codominant sugarberry trees from near Stoneville, Mississippi stemwood specific gravity 10 feet above ground level was significantly less than at the 5-foot level. Above 10 feet the relationship between height and specific gravity was inconsistent, but generally specific gravity at the 40-foot level was higher than at 20 or 25 feet (fig. 7-14).

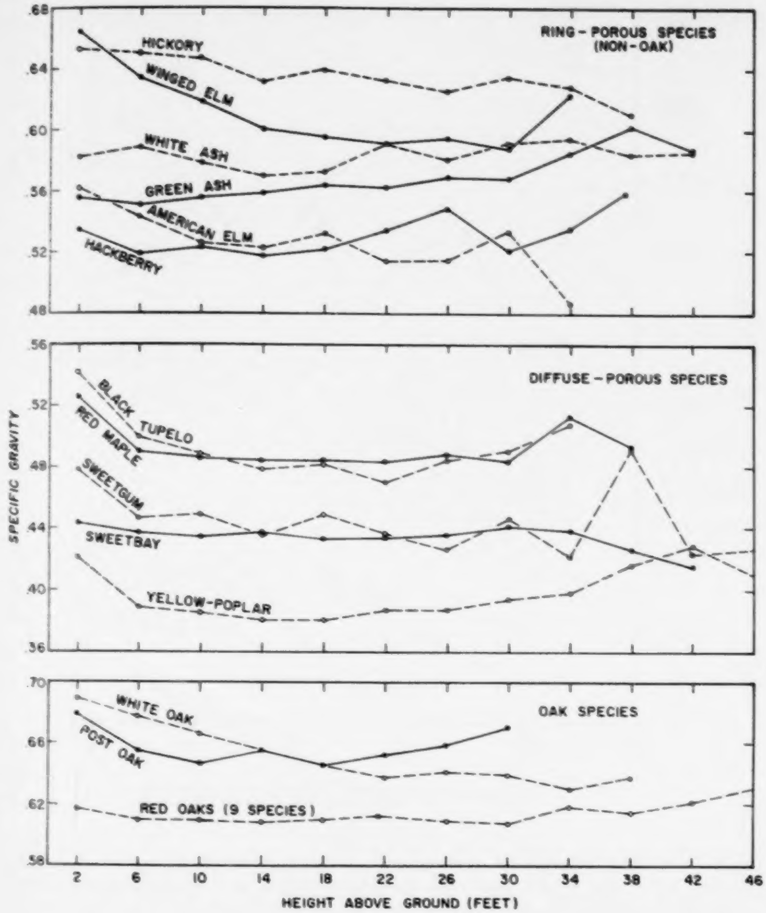

Figure 7-13.—Relationships between height in 6-inch hardwoods grown on southern pine sites and stemwood specific gravity (basis of unextracted ovendry weight and green volume). Each curve is the average for 10 trees, except for the bottom curve which is the average of 90 trees representing nine species of red oaks. See table 3-1 for additional tree data. (Drawing after Manwiller 1979.)

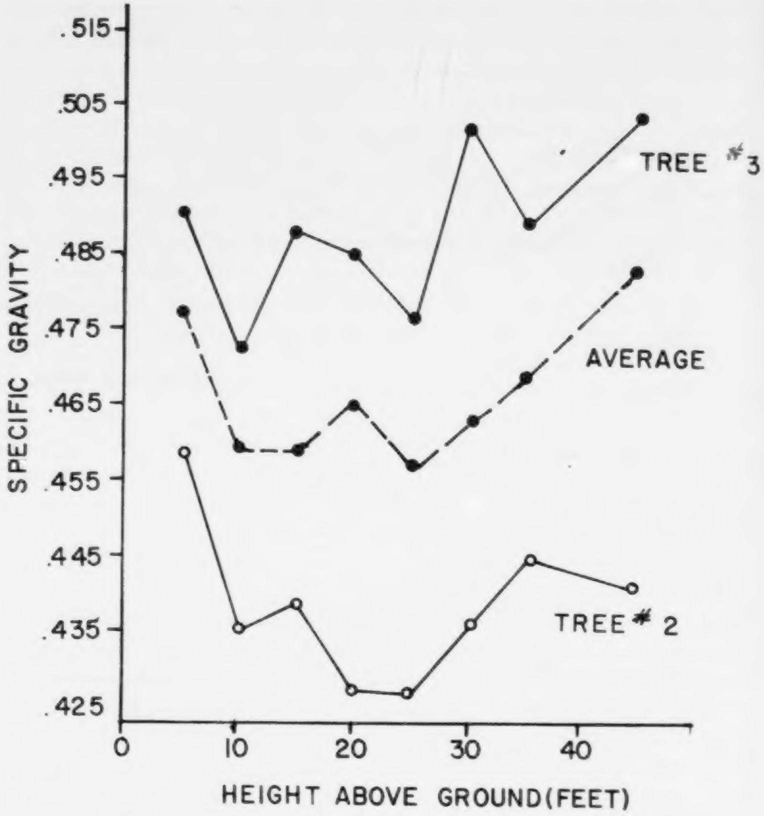

Figure 7-14.—Relationship between stemwood specific gravity (unextracted ovendry weight and green volume basis) and height above ground in sugarberry trees. Average data plots are based on twelve trees. Upper and lower plots represent trees of highest and lowest specific gravity. (Drawing after Taylor 1971.)

Radial variation was also substantial in these trees; in the most uniform of the six trees the most-dense annual ring had specific gravity 0.11 higher than that of the least-dense. Up to 35-feet in height, specific gravity decreased with increasing number of rings from the pith; at 45 feet, however, the relationship was curvilinear, with specific gravity increasing between rings 11 and 17 (fig. 7-15).

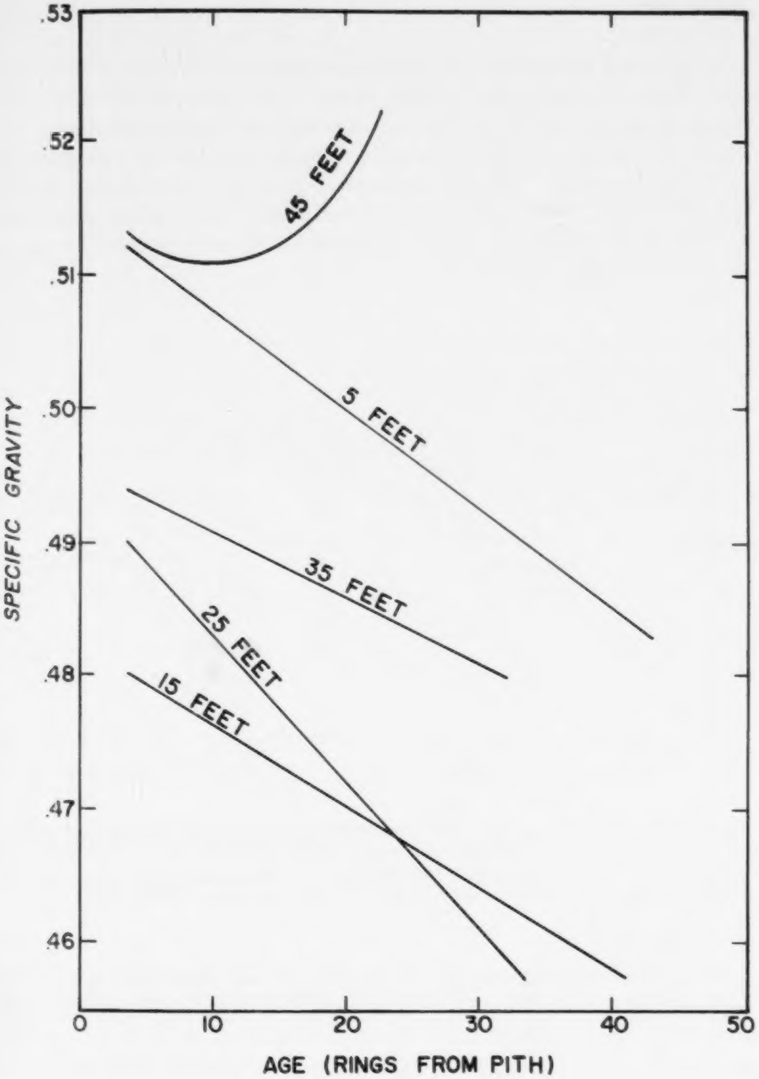

Figure 7-15.—Radial variation in stemwood specific gravity (unextracted ovendry weight and green volume basis) at five heights in sugarberry trees. Ages were counted from pith at indicated heights. Regression plots are based on data from twelve trees; correlation coefficients ranged from 0.66 to 0.85. (Drawing after Taylor 1971.)

HICKORY

Stemwood of 6-inch true hickory trees sampled Southwide from southern pine sites (table 7-7) had higher specific gravity (0.64) than that of branchwood (0.61); stemwood specific gravity was inversely correlated with height in tree (fig. 7-13). Taylor's (1977b, 1979) study of 11-inch hickories—12 shagbark and 12 mockernut—from Arkansas, Louisiana, Mississippi, and Alabama showed that stemwood specific gravity (0.675) was higher than that of branchwood (0.645); stemwood specific gravity increased slightly with increasing height in tree, however (fig. 7-16).

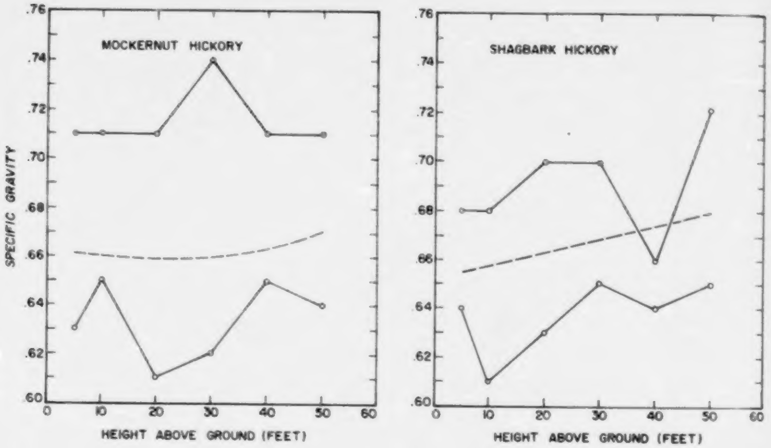

Figure 7-16.—Relationship between stemwood specific gravity (unextracted ovendry weight and green volume basis) and height above ground in two species of hickory. Each dashed line is fitted to data from twelve trees; upper and lower curves represent trees of highest and lowest specific gravity. (Drawing after Taylor 1979.)

Radial variation in specific gravity of hickory is correlated in a complex way with width of growth rings (fig. 7-7); in brief, any noticeable decrease in width of annual rings appears to coincide with formation of wood of low specific gravity (fig. 7-17). In old-growth pignut hickory trees sampled in North Carolina, Paul (1929) observed that the specific gravity of heartwood (0.62) was greater than in sapwood (0.50).

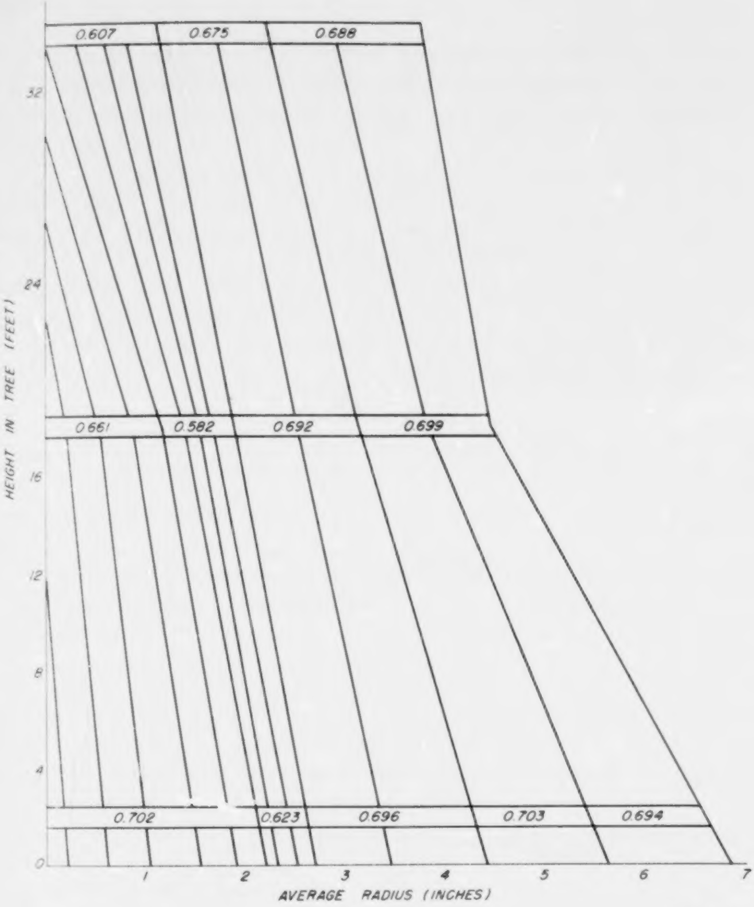

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Figure 7-17.—Radial variation in specific gravity (unextracted ovendry weight and green volume basis) at three heights in stemwood of pignut hickory. The diagonal lines mark each 10-year growth period in the 130-year-old tree. (Drawing after Paul 1963.)

Taylor's (1979) breast-height sample of 24 hickory trees from the Mid-South showed increasing specific gravity with increasing number of rings from the pith up to age 28 (fig. 7-18); after that age, the increase in mockernut slowed and in shagbark specific gravity diminished to a level approaching that near the pith. Boisen and Newlin (1910) concluded from 1,094 small samples of hickory that specific gravity remained approximately uniform from pith to a radius of about 6 inches, and then diminished slightly out to a radius of 11 inches.

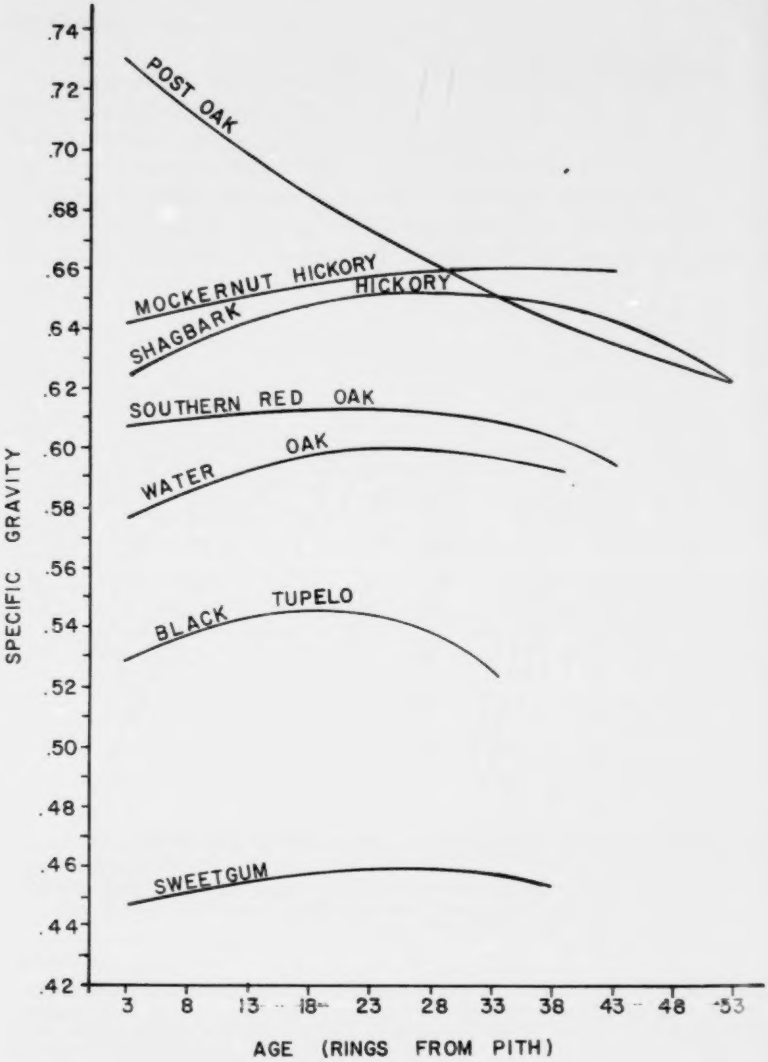

Figure 7-18.—Relationship between stemwood specific gravity (unextracted ovendry weight and green volume basis) five feet above ground level in seven hardwood species and number of annual rings distant from tree pith. Each plot contains data from 12 trees averaging about 11 inches dbh sampled in the Mid-South. (Drawing after Taylor 1979.)

MAPLE, RED

In 6-inch red maple trees from southern pine sites sampled Southwide (table 7-7), branchwood had about the same specific gravity as stemood; in these trees, stemwood sections located 6 to 30 feet from ground level had lowest specific gravity (fig. 7-13).

In 71 larger red maples sampled throughout the Piedmont and Atlantic and Coastal Plain, Kellison and Zobel (1971) found that wood specific gravity at breast height was slightly higher (0.47) than the weighted average for entire stemwood (0.46). Specific gravity in 1-year-old red maple sprouts did not vary appreciably between internodes, except at the last-formed internodes near the apex, where it decreased rapidly (Saucier and Taras 1966).

Data on radial variation of specific gravity in red maple stemwood are not available.

OAKS

Branchwood and stemwood.—In 6-inch oak trees sampled from southern pine sites Southwide, specific gravity of branchwood of laurel oak and blackjack oak exceeded that of stemwood by 0.042 and 0.068, respectively. On the basis of averages from table 7-7, an additional six species had branchwood of slightly higher specific gravity than stemwood; only in white oak, post oak, and northern red oak did branch wood specific gravity average lower than that of stemwood.

From 50 35-year-old northern red oak, Hamilton et al. (1976) observed that branchwood specific gravity was higher but more variable, than that of stemwood. Branches highest in the crown had higher specific gravity than those lower in the crown (fig. 7-19). In all crown positions, branchwood specific gravity decreased from point of union outward.

Wood specific gravities of sawlog, pulpwood, top and branch portions of 6- to 22-inch-dbh northern red, scarlet, southern red, and chestnut oaks from the Southeast are given in table 7-2A.

Taylor (1977b), in a sample of three oak species from four Midsouth States, found that branchwood averaged slightly higher in specific gravity, as follows:

Species	Specific gravity	
	Stemwood	Branchwood
Post oak	0.64	0.66
Southern red oak	.61	.64
Water oak	.60	.62

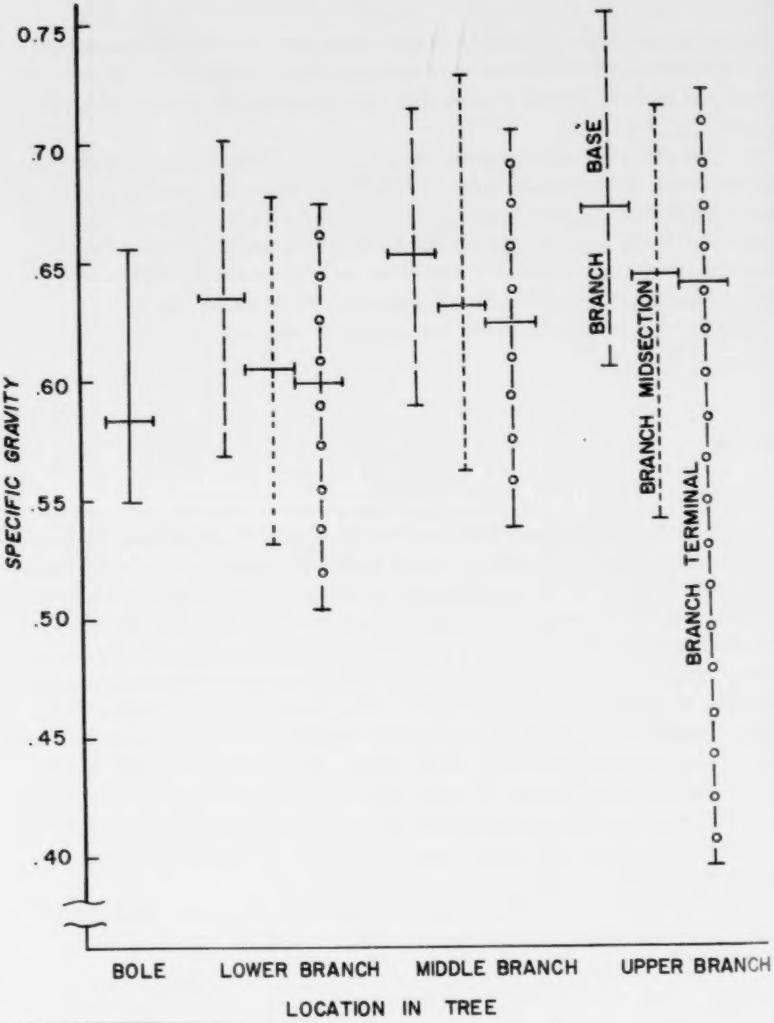

Figure 7-19.—Specific gravity (unextracted ovendry weight and green volume basis) of stemwood and lower, middle, and upper branchwood of 35-year-old northern red oak sampled near Morgantown, West Virginia. Data are based on 50 trees. (Drawing after Hamilton et al. 1976.)

Variation with height in stem.—From 94-year-old **black oak** and 67-year-old **scarlet oak** sampled in Missouri, McGinnes and Ralston (1967) concluded that crown-formed stemwood (juvenile wood) was of highest specific gravity. Specific gravity patterns within stemwood of **black oak** vary with vigor of growth; trees in thrifty young stands have higher stemwood density than that of trees growing in suppressed stands (fig. 7-20). In general, oak stemwood has highest specific gravity in the lower butt section and in upper stem sections; at 10- to perhaps 20-foot levels, stemwood specific gravity is lower (fig. 7-13). In the **red oak group,** for example, Paul (1942) found that heartwood just above the stump was least porous, with increasing vessel volume up to 15 to 20 feet; from that point upward, there was a decrease in vessel volume in some species.

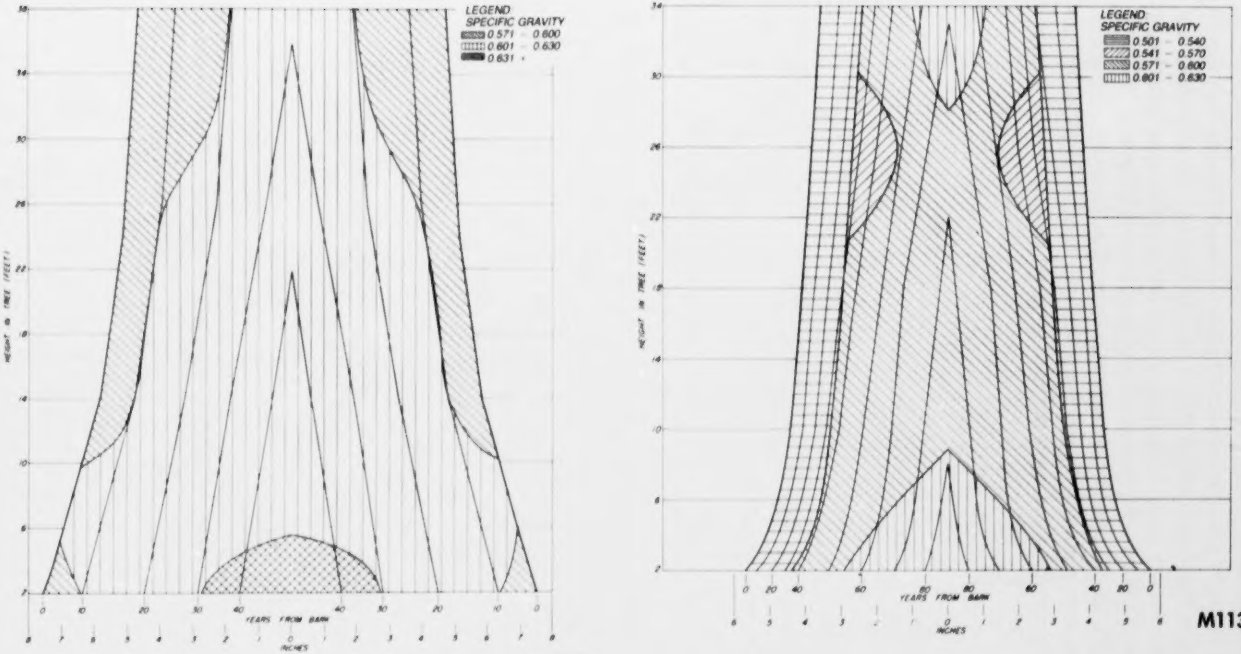

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Figure 7-20.—Variation of stemwood specific gravity (unextracted ovendry weight and green volume basis) in black oak, with radial position and height in stem. (Left) Second-growth trees from a thrifty young stand grown at a uniform rate. (Right) Second-growth trees retarded in growth rate **for last 40 years. Each diagram is based on data from five trees. (Drawings after Paul 1963.)**

Taylor's (1979) data on 11-inch post oak, southern red oak, and **water oak** sampled in the Mid-South indicate that stemwood sections 40 feet above ground level have slightly higher specific gravity than those at the 20-foot level, but patterns are highly variable (fig. 7-21).

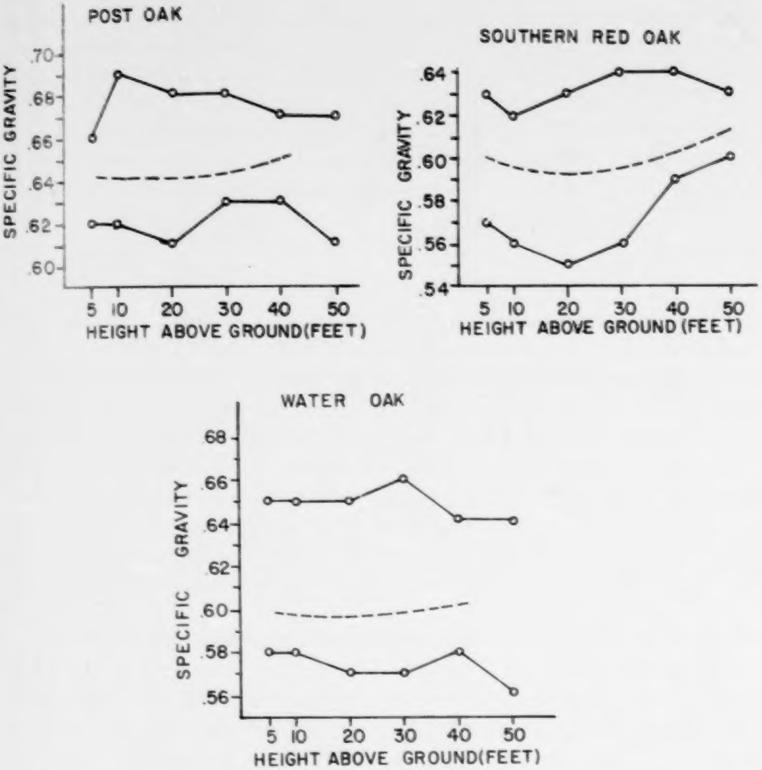

Figure 7-21.—Relationship between stemwood specific gravity (unextracted ovendry weight and green volume basis) and height above ground in three oak species. Average data plots are based on 12 trees. Upper and lower plots represent trees of highest and lowest specific gravity. (Drawing after Taylor 1979.)

Breast-height stemwood of **water oak** and willow oak trees sampled throughout the Piedmont and Atlantic and Gulf Coastal Plain had the same specific gravity (0.59) as weighted tree stemwood, indicating little variation with height in these species (Kellison and Zobel 1971). No separation was made between the two species in this study.

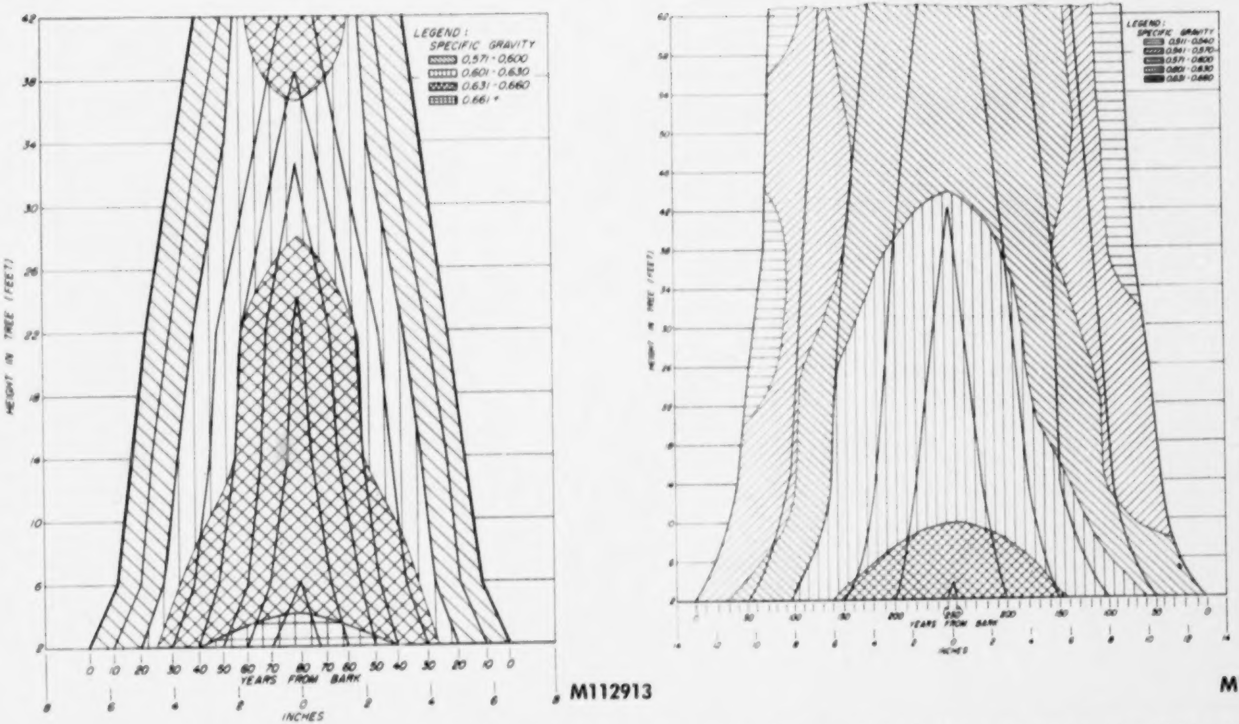

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Figure 7-22.—Variation in stemwood specific gravity (unextracted ovendry weight and green volume basis) of white oak, with radial position and height in stem. (left) Second-growth. (Right) Old-growth. Each diagram is based on data from five trees. (Drawings after Paul 1963.)

White oak stemwood is dense near ground level and may be less dense 20 or 30 feet above ground level (figs. 7-13 and 7-22).

Variation with radial position.—In butt logs from fifteen 90-year-old **black oak** trees and from thirteen 70-year-old **scarlet oak** trees grown in Missouri, specific gravity was maximum near the pith (about 0.58) and decreased more-or-less linearly to about 0.51 at age 70; in these logs, McGinnes and Ralston (1967) found that the percent of each annual ring made up of an earlywood pore zone was minimum near the pith and maximum at the bark. Variation among logs sampled was substantial; specific gravity of fast-grown wood averaged about 0.57, while that of slow-grown wood was significantly lower (0.52).

Stemwood specific gravity of **chestnut oak** 47 to 59 years old was also found inversely correlated with percent earlywood and positively correlated with percent latewood as follows (Bethel 1943):

$$\text{Specific gravity} = .3129 + \frac{.60 \text{ x percent latewood}}{100} \qquad (7\text{-}6)$$

Sachs et al. (1966) found that heartwood of **northern red oak** logs had higher specific gravity (0.77) than that of sapwood (0.71).

Taylor's (1979) data on breast-height samples from 11-inch **post oak, southern red oak,** and **water oak** trees (fig. 7-18) show varying patterns of radial variation. In post oak, specific gravity was highest near the pith (0.73) and lowest near the bark (0.63). Water oak, however, had lowest specific gravity near the pith, with maximum occurring in the 25th ring. Southern red oak showed little radial variation in stemwood specific gravity at the 5-foot level. Its pattern of variation at 30-feet above ground level approximated that of post oak, i.e., wood near the bark was substantially less dense than that near the pith (fig. 7-23).

Hamilton's (1961) analysis of six **southern red oaks** from mixed hardwood-pine stands in Durham County, North Carolina showed that even in lower stem sections specific gravity of stemwood was inversely correlated with number of rings from the pith; this significant diminution of specific gravity was accompanied by a slight diminution in percentage of latewood. Figure 7-24 diagrams specific gravity variations in southern red oak with both radial and vertical position in a stem.

In most **white oaks** studied by Paul (1963) there was a trend of lessening specific gravity and narrowing ring width, from pith toward the bark (fig. 7-22). In some trees, however, ring widths were maintained or increased with increased age; in such trees specific gravity values were fairly constant throughout a cross section.

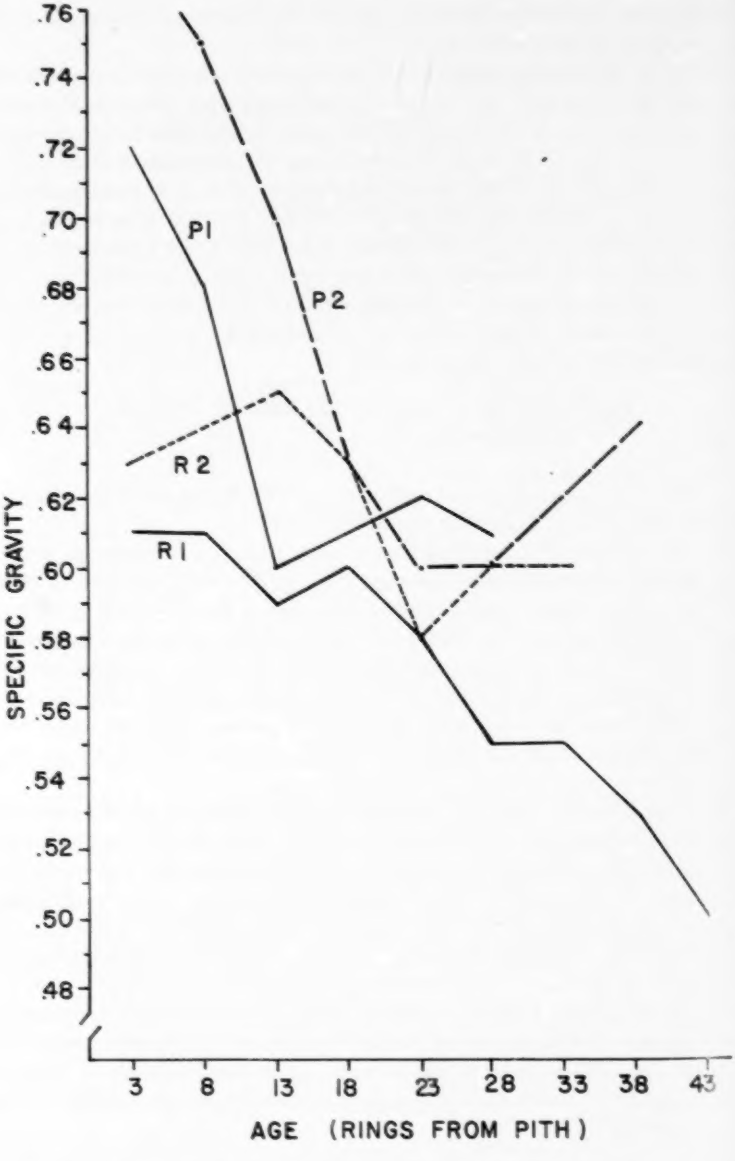

Figure 7-23.—Relationship between number of rings from the pith and specific gravity (unextracted ovendry weight and green volume basis) of stemwood sampled 30 feet above ground level in two southern red oak trees (R_1 and R_2) and two post oak trees (P_1 and P_2). Drawing after Taylor 1979.)

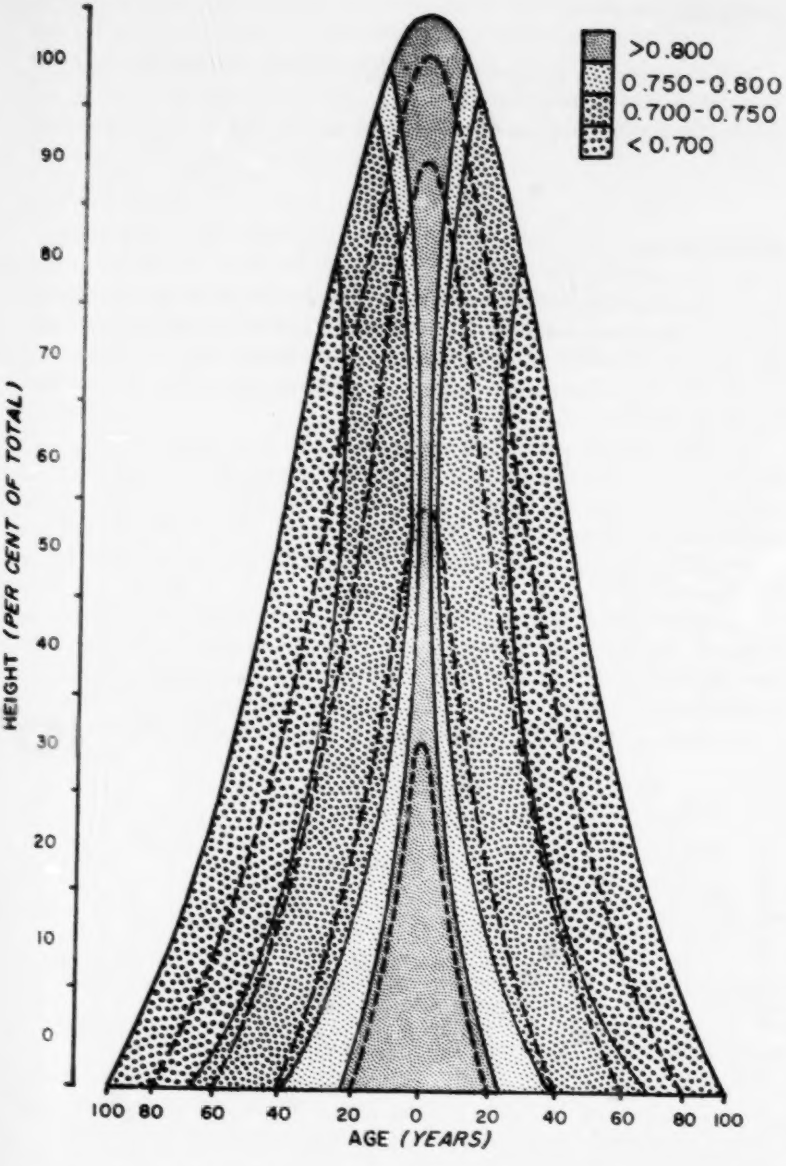

Figure 7-24.—Variation in specific gravity (basis of unextracted ovendry weight and ovendry volume) in stemwood of southern red oak. Data are based on the average of six trees. (Drawing after Hamilton 1961.)

SWEETBAY

In 6-inch sweetbay sampled from southern pine sites Southwide (table 7-7), branchwood had slightly lower specific gravity (0.42) than stemwood (0.44); height above ground was not correlated with specific gravity of stemwood (fig. 7-13).

SWEETGUM

Ezell and Schilling (1980) found from study of nine upland and nine bottomland sweetgum trees sampled in the Midsouth, that specific gravity varied with height and year of deposition, but patterns were not consistent within or among trees. Others have found certain patterns of variation, as described in the following paragraphs.

In 6-inch sweetgum sampled from southern pine sites Southwide (table 7-7) branchwood had the same specific gravity (0.45) as stemwood. In trees 6 to 22 inches in dbh from the Georgia Piedmont, branchwood had higher specific gravity than stemwood (table 7-2A). In the Midsouth, Taylor (1977b) found that sweetgum stemwood in 11-inch trees had specific gravity of 0.46, that of branchwood 0.48.

Variation with height in stem.—From a sample of six dominant and codominant sweetgum trees growing near Raleigh, North Carolina, Webb (1964) concluded that specific gravity was near maximum at stump height, decreased to a minimum 20 feet above ground, and then increased; upland trees displayed more variation with height in stem than did bottom land trees (fig. 7-25).

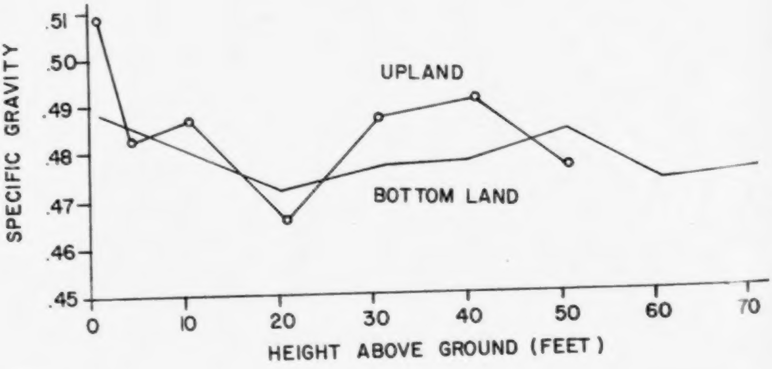

Figure 7-25.—Variation in specific gravity (unextracted ovendry weight and green volume basis) of sweetgum stemwood with height above ground. Each curve is based on data from three trees sampled in North Carolina; upland trees were 23 to 28 years old and the bottom land trees ranged from 35 to 43 years old. (Drawing after Webb 1964.)

Thirty bottom land sweetgum trees.—10 each from stands near Vicksburg, Greenville, and Clarksdale, Mississippi—had a similar pattern of variation, as follows (Carpenter and Hopkins, 1966):

Location in stem	Stemwood Specific gravity
2-foot level	0.511
18-foot level	.500
Mid-point of crown	.518

Fifteen dominant, co-dominant, or open-grown sweetgum trees between the ages of 25 and 45 years sampled near Bainbridge, Georgia had patterns of specific gravity variation with height similar to the upland trees from North Carolina. Specific gravity was maximum at stump height, decreased rapidly to around 10 feet, increased, and then decreased again (fig. 7-26), a pattern similar to that exhibited by yellow-poplar.

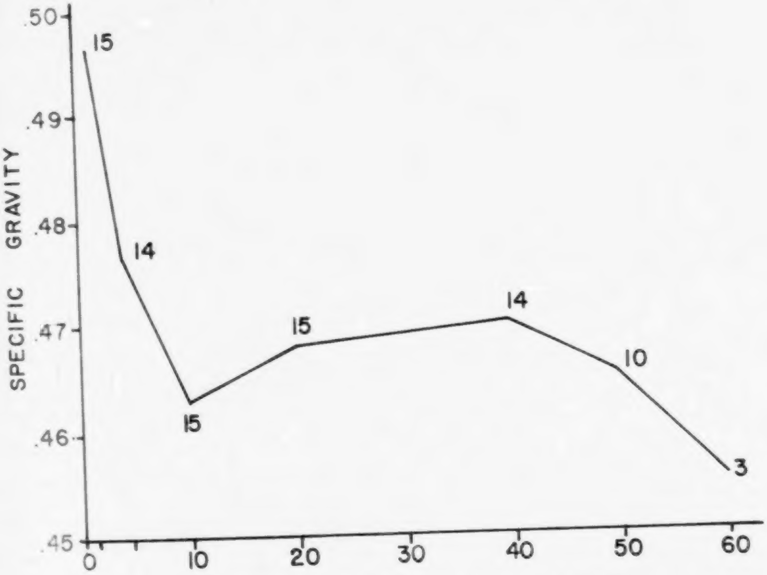

Figure 7-26.—Variation in specific gravity (unextracted ovendry weight and green volume basis) of sweetgum stemwood sampled near Bainbridge, Georgia, with height above ground. The plot is based on data from the number of trees indicated. (Drawing after Webb 1964.)

Similar patterns of stemwood density variation were observed by Taylor (1979) in a total of 12 sweetgum trees averaging about 11 inches dbh sampled from six locations in the Mid-South (fig. 7-27).

Six-inch sweetgum trees from southern pine sites had maximum stemwood specific gravity near ground level and at the 38-foot level (fig. 7-13).

In Webb's (1964) study of Georgia sweetgum, specific gravity of breast-height core segments provided a good estimate of entire stemwood specific gravity; stemwood specific gravity was about 0.01 less than specific gravity of rings 11 through 20 sampled at breast height. This same relationship was observed by Kellison and Zobel (1971) in a sample of 76 sweetgum trees throughout the Piedmont and Atlantic and Gulf Coastal Plain.

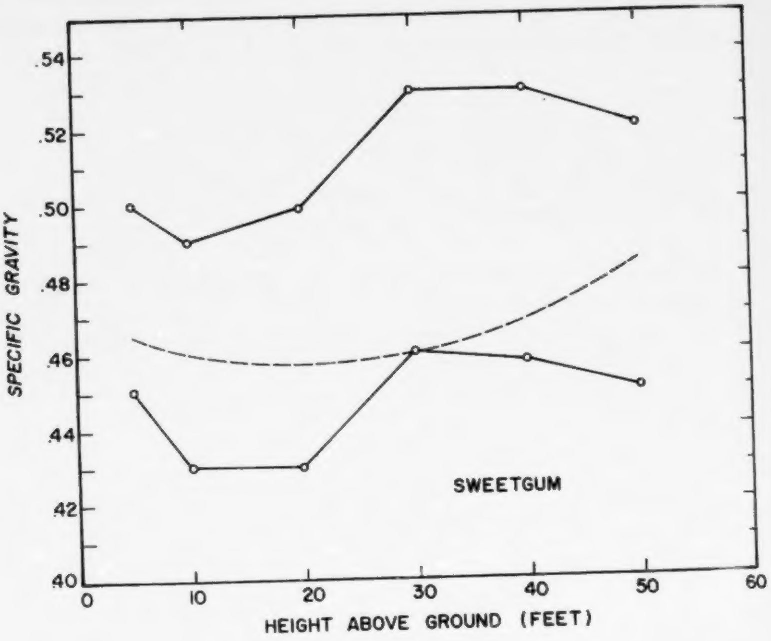

Figure 7-27.—Specific gravity (unextracted ovendry weight and green volume basis) of Mid-South sweetgum stemwood related to sampling height within the stem. The dashed line is fitted to data from 12 trees; upper and lower plots represent trees of highest and lowest specific gravity. (Drawing after Taylor 1979.)

Variation with radial position.—When analyzed at breast height, sweetgum trees have lowest wood specific gravity near the pith and maximum in about the 15th to 25th ring (figs. 7-18 and 7-28). Averaged over 10 rings or more, the variation at breast height may not be great, however, as follows:

	Data source	
Sample portion and description	McElwee et al. (1970)	Johnson and McElwee (1967)
Rings 1-10, specific gravity	0.49	0.48
Rings 11 +, specific gravity	.50	.50
Number of trees	25	140
Geographic locations	Georgia (Hancock Co.)	Piedmont and Atlantic and Gulf Coastal Plain

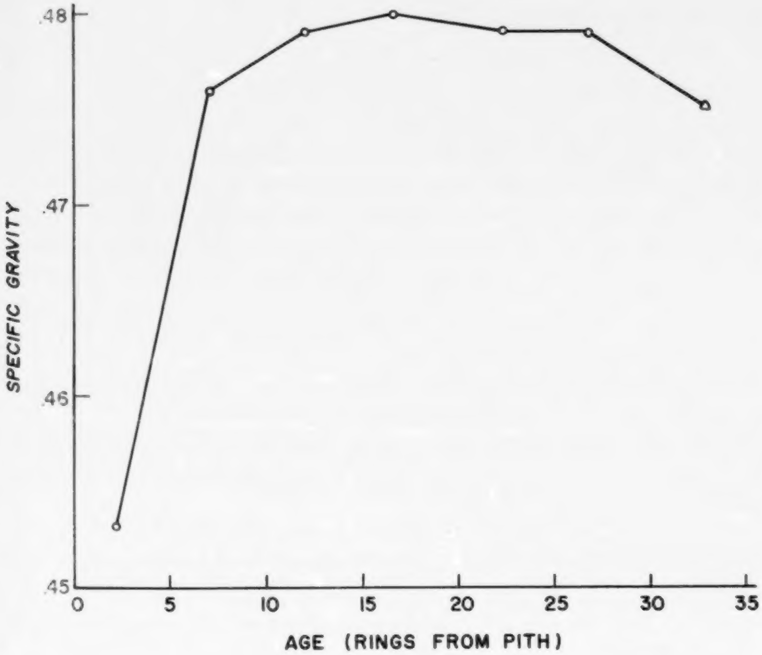

Figure 7-28.—Variation in specific gravity (unextracted ovendry weight and green volume basis) of sweetgum stemwood at breast height with radial position. Circled data points based on 15 trees, triangle point based on nine trees—all from near Bainbridge, Georgia. (Drawing after Webb 1964, 1965.)

TUPELO, BLACK

In 6-inch black tupelo sampled from southern pine sites Southwide (table 7-7) branchwood had slightly lower specific gravity (0.49) than stemwood (0.50). Stemwood specific gravity was maximum near ground level and minimum 10 to 30 feet above ground level (fig. 7-13).

Twelve black tupelo trees averaging about 11 inches dbh sampled from six locations (two per location) throughout the Mid-South, had highest stemwood specific gravity near the ground, with lower values at 20 to 40 feet; topmost stem sections averaged slightly higher in specific gravity than those of intermediate height (fig. 7-29); branchwood and stemwood had about the same specific gravity—0.51 and 0.52, respectively (Taylor 1977b).

In these same 12 trees, breast-height stemwood samples had maximum specific gravity at about 18 rings from the pith; younger wood and older wood had lower specific gravity (fig. 7-18).

YELLOW-POPLAR

Six-inch yellow-poplar from southern pine sites sampled Southwide (table 7-7) had branchwood of slightly higher specific gravity (0.41) than that of stemwood (0.40). Similar values were reported by Clark and Schroeder (1975) for 39 yellow-poplar trees from western North Carolina that ranged from 6 to 28 inches in dbh; in these larger trees, branchwood specific gravity was 0.42 and stemwood specific gravity 0.41. In 11-inch-dbh yellow-poplar from four Midsouth States, Taylor (1977b) found that branchwood specific gravity was 0.50 and stemwood specific gravity 0.46.

Variation with height in stem.—Clark et al. (1974) sampled 47 yellow-poplar trees, 56 to 99 years old and 11.7 to 28.4 inches dbh, from a mountain-cove, natural stand in western North Carolina; wood in saw-log portions had lower specific gravity (0.41) than that of the pulpwood portion (0.43) or topwood portion (0.44).

Clark and Schroeder's (1977) analysis of 39 trees measuring 6 to 28 inches in diameter yielded the following data on specific gravity, moisture content, and weight of yellow-poplar wood in western North Carolina (table 7-2A):

Tree component	Specific gravity	Moisture content	Green weight per cubic foot
Total tree	0.407	104	51.8
Total stem	.407	104	51.8
Sawlog section	.406	103	51.5
Pulpwood section	.413	103	52.3
Topwood section	.419	111	55.2
Branches	.424	106	54.4

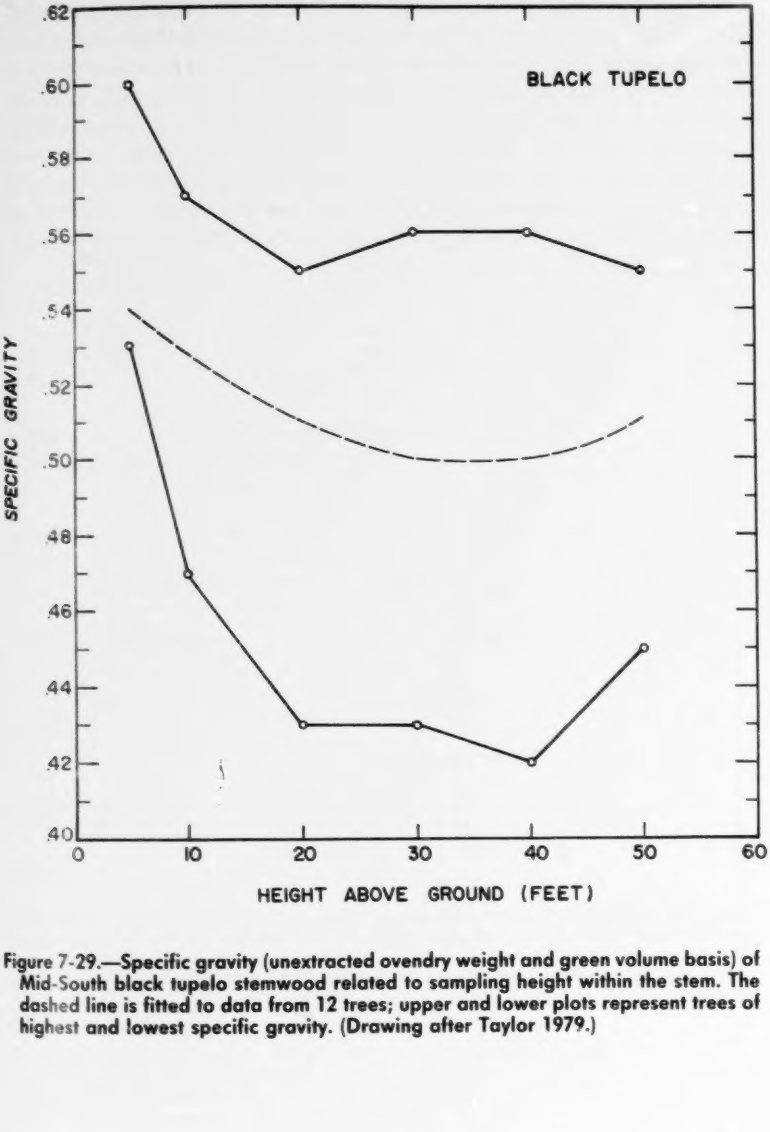

Figure 7-29.—Specific gravity (unextracted ovendry weight and green volume basis) of Mid-South black tupelo stemwood related to sampling height within the stem. The dashed line is fitted to data from 12 trees; upper and lower plots represent trees of highest and lowest specific gravity. (Drawing after Taylor 1979.)

This variation results from patterns typical of yellow-poplar stemwood, in which specific gravity is highest per near ground level and decreases rapidly to a near minimum at about the 10-foot level, then levels off with increased height to a low value between 30 and 50 feet; above this zone, specific gravity increases again (figs. 7-13, -30, -31, -32, and -33). At 70 feet stemwood specific gravity may exceed that at breast height (Taylor 1968). Decline of specific gravity with height was confirmed by Yakub (1971) who found stemwood specific gravity of 0.44 at ground level and only 0.38 at 20 feet in northern West Virginia, and by Gilmore (1971) who also observed diminution in stemwood specific gravity from breast height to 20 feet.

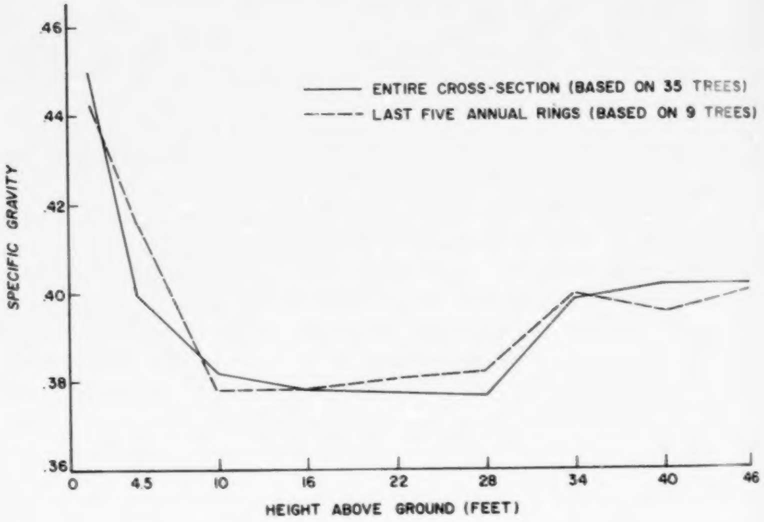

Figure 7-30.—Variation of stemwood specific gravity (unextracted ovendry weight and green volume basis) with height above ground level in yellow-poplar trees averaging 11 inches in dbh and 30 years old. Data are based on trees sampled at elevations from 1,600 to 2,500 feet above sea level in northern West Virginia. (Drawing after Koch et al. 1968.)

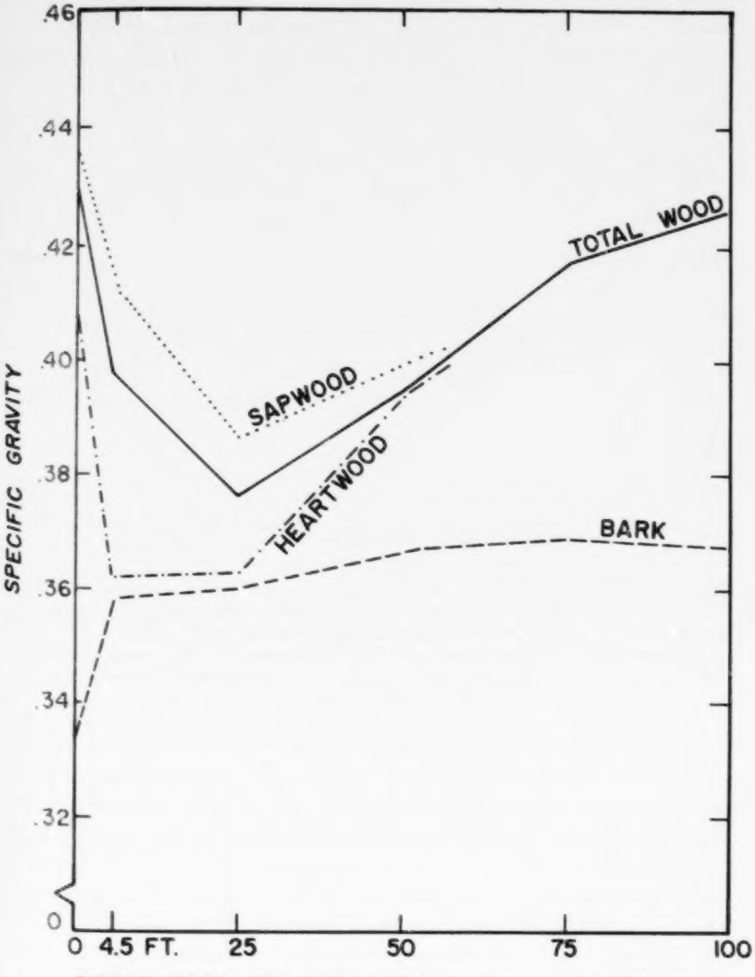

Figure 7-31.—Variation in specific gravity (unextracted ovendry weight and green volume basis) of bark and wood with height in yellow-poplar trees 9.5 to 10.5 inches in dbh and 50 years old. Data are based on 60 codominant and intermediate trees from western North Carolina (Schroeder and Phillips 1973.)

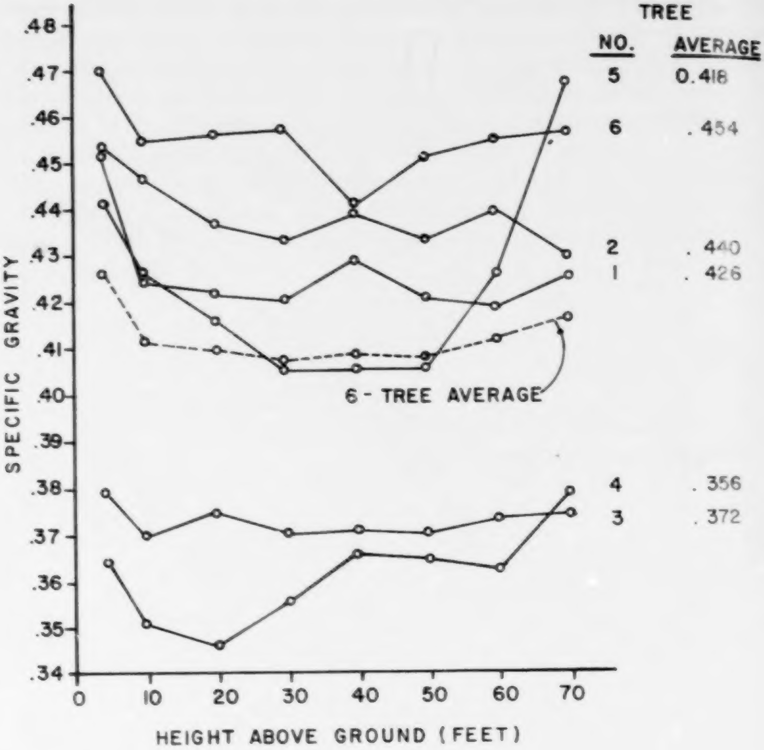

Figure 7-32.—Relationship between height in six yellow-poplar trees and stemwood specific gravity (unextracted ovendry weight and green volume basis). Trees were 50- to 60-year-old dominants from the North Carolina Piedmont. (Drawing after Taylor 1965, 1968.)

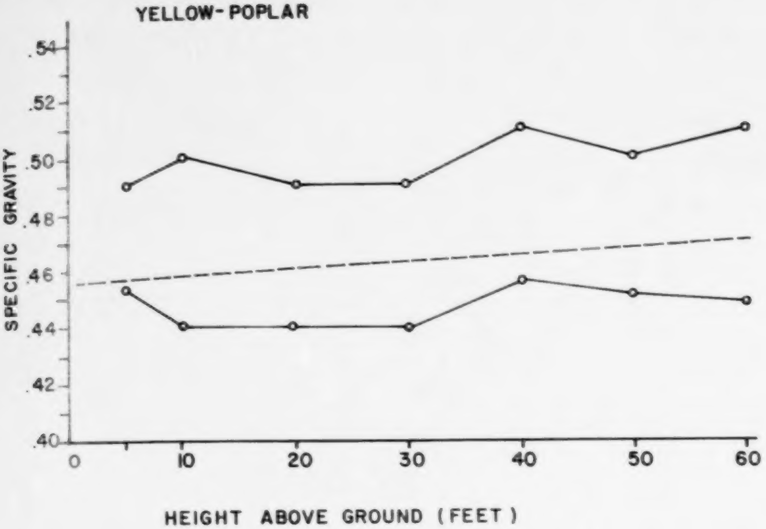

Figure 7-33.—Relationships between stemwood specific gravity (unextracted ovendry weight and green volume) in 11-inch yellow-poplar and height above ground. Dashed line is fitted to data from six trees sampled on three plots throughout the Midsouth. Upper and lower plots represent trees of highest and lowest specific gravity. (Drawing after Taylor 1979.)

Variation with radial position.—Radial variation in specific gravity of yellow-poplar stemwood follows a relationship with interactions between height in stem and number of rings from the pith. At breast height, least dense wood is near the pith and specific gravity increases with increasing number of rings from the pith with a maximum occurring 35 to 50 years out (Thorbjornsen 1961, Taylor 1964, Sluder 1972). At 60 feet, however, specific gravity decreases with increased number of rings from the pith (figs. 7-34 and 7-35).

Weight of yellow-poplar sawtimber.—A sample of 230 sawlogs cut in North Carolina from 47 yellow-poplar trees (averaging 19.3 inches dbh and 62 feet to an 8-inch top) had average wood specific gravity of 0.415 and moisture content of 94 percent; wood from these sawlogs therefore had an average green weight of 50.2 pounds per cubic foot (Clark 1976).

Yellow-poplar 12 to 28 inches in dbh from western North Carolina had average green stem weight (including bark) of 49.4 pounds per cubic foot; green crown material (including bark) averaged 56.0 pounds per cubic foot. A cubic foot of stem material contained 21.2 pounds of dry wood, 3.5 pounds of dry bark, and 24.7 pounds of water, compared to a cubic foot of crown material which contained 18.7 pounds of wood, 5.9 pounds of bark, and 31.4 pounds of water (Clark and Schroeder 1975).

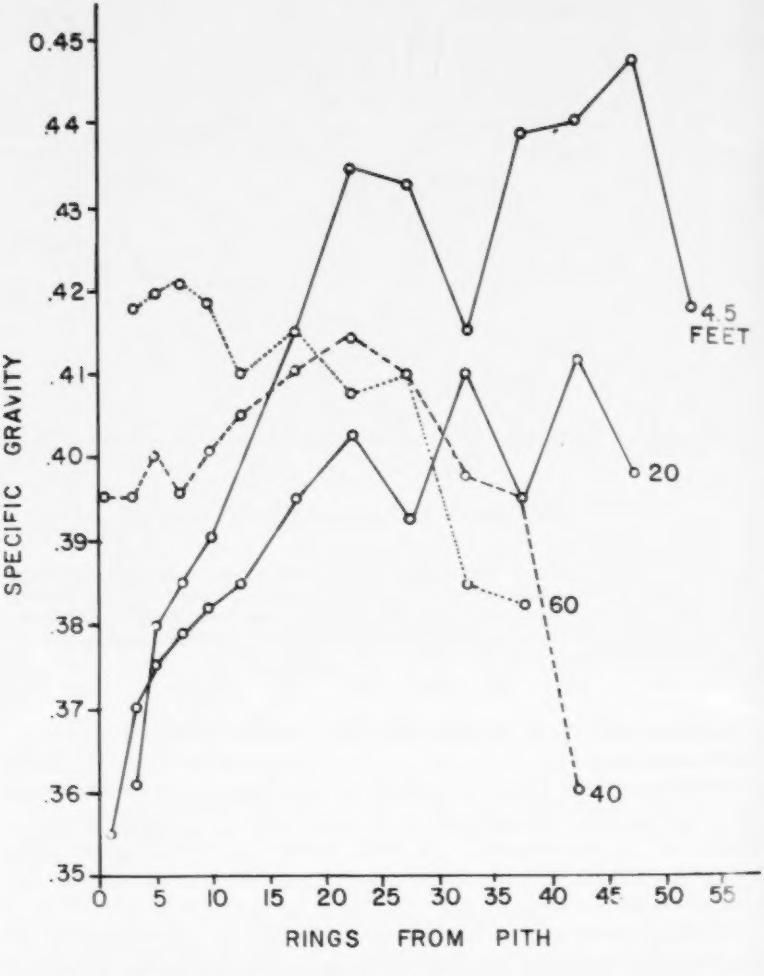

Figure 7-34.—Relationship of stemwood specific gravity (unextracted ovendry weight and green volume basis) in yellow-poplar trees to number of rings from the pith at four heights above ground. Data are based on six dominant trees from the Piedmont of North Carolina. (Drawing after Taylor 1965, 1968.)

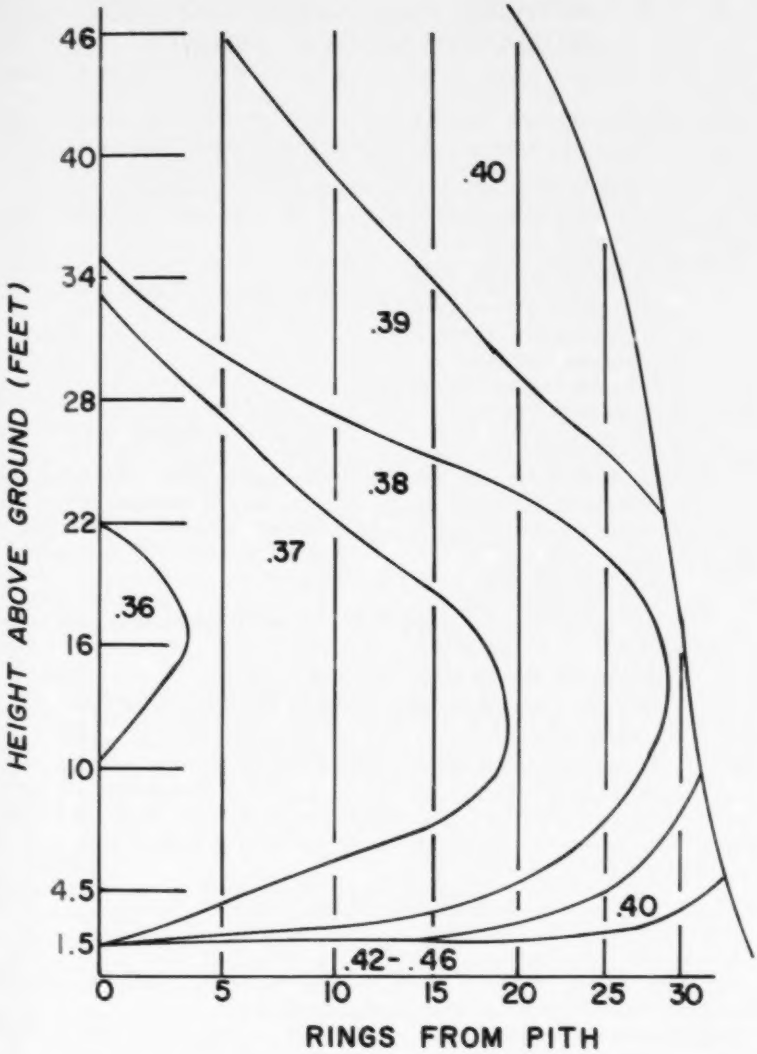

Figure 7-35.—Variation in specific gravity (unextracted ovendry weight and green volume basis) of yellow-poplar stemwood with radial position and height in tree. See figure 7-29 for sample details (Drawing after Koch et al. 1968.)

7-7 METHODS FOR COMPUTING AND ESTIMATING SPECIFIC GRAVITY

It is not the purpose of this text to dwell on methodology; however, the interested reader may wish to pursue the subject. Some references follow:

- To measure small pieces of wood
    - Paul and Baudendistel (1943)
    - Heinrichs (1954)
    - Smith (1954, 1961, 1965)
    - U.S. Department of Agriculture, Forest Service (1956)
    - Browning (1967, chap. 18)
    - Wangaard (1969)
    - Heinricks and Lassen (1970)
    - Julien et al. (1971)
    - Harder (1976)
- To measure density profiles
    - Parker and Pozsa (1977)
- To measure logs, flitches, and bolts
    - Pillow (1951)
    - Pronin (1966)
- To estimate average specific gravity of an entire species or large block of timber
    - By random sample: Bendsten (1968)
    - By random sample stratified according to age and growth rate: Manwiller (1972)
    - By random sample of breast-height increment cores: Taras and Saucier (1968)

7-8 BULK DENSITIES

Bulk densities of particulate wood and bark in various forms are given in section 16-13, table 13-42, and in related discussion.

Bulk densities of wood and bark in place are given in tables 7-2, 7-2A, and 13-40.

7-9 LITERATURE CITED

Aldridge, F. and Hudson, R. H. 1954. Growing timber quality ash. Quart. J. For. 48:210-214.

Barefoot, A. C., Jr. 1958. Critical properties of second growth wood and abnormal wood in yellow-poplar (*Liriodendron tulipifera* L.). D. F. thesis. Sch. of For., Duke Univ., Durham, N. C. 160 p.

Barefoot, A. C., Jr. 1963. Selected wood characteristics of young yellow poplar (*Liriodendron tulipifera* L.). Part II. Shrinkage of normal and abnormal wood. For. Prod. J. 13:443-448.

Baudendistel, M. E. and B. H. Paul. 1944. Southern hard elms as substitutes for rock elm. South. Lumberman 169(2129):211-215.

Beall, F. C. 1972. Density of hemicelluloses and their relationship to wood substance density. Wood and Fiber 4(2):114-116.

Bendtsen, B. A. 1968. Mechanical properties and specific gravity of a randomly selected sample of spruce pine. U.S. Dep. Agric. For. Serv., Res. Pap. FPL-92. 8 p.

Bendtsen, B. A. and R. L. Ethington. 1975. Mechanical properties of 23 species of eastern hardwoods. U.S. Dep. Agric. For. Serv., Res. Note FPL-0230, 12 p.

Benic, R. 1955. Growth-ring width as a factor in the quality of *Fraxinus angustifolia* wood. Sumarstvo, (Beograd) 8:534-545.

Bethel, J. S. 1943. Factors influencing the specific gravity of chestnut-oak wood. J. For. 41:509-601.

Boisen, A. T. and J. A. Newlin. 1910. The commercial hickories. U.S. Dep. Agric. For. Serv., Bull. 80. 64 p.

Browning, B. L. 1967. Methods of wood chemistry. Vol. 1, 384 p. N. Y.: Interscience Pub.

Carpenter, B. E., Jr. and W. C. Hopkins. 1966. Specific gravity values of sweetgum topwood and bolewood. For. Prod. J. 16(7): 30.

Choong, E. T. and P. J. Fogg. 1976. Extractives content and cell-wall specific gravity in sweetgum. LSU Wood Util. Notes No. 30, 4 p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A & M Coll., Baton Rouge, La.

Clark, A. III. 1976. Sawmill residue yields from yellow-poplar saw logs. For. Prod. J. 26(1):23-27.

Clark, A. III and J. G. Schroeder. 1975. Aboveground biomass of yellow-poplar in a natural sawtimber stand in western North Carolina. *In* Impact of inflation on the management and utilization of hardwoods, proc. of the third annu. hardwood symp. of the Hardwood Res. Counc., pp. 32-33.

Clark, A. III, and J. G. Schroeder. 1977. Biomass of yellow-poplar in natural stands in western North Carolina. U.S. Dep. Agric. For. Serv. Res. Pap. SE-165. 41 p.

Clark, A. C. III, M. A. Taras, and J. G. Schroeder. 1974. Predicted green lumber and residue yields from the merchantable stem of yellow-poplar. U.S. Dep. Agric. For. Serv., Res. Pap. SE-119. 15 p.

Clark, A. III, D. R. Phillips, and J. G. Schroeder. 1980a. Predicted weights and volumes of northern red oak trees in western North Carolina. Res. Pap. SE-209, U.S. Dep. Agric., For. Serv., 22 p.

Clark, A. III, D. R. Phillips, and H. C. Hitchcock III. 1980b. Predicted weights and volumes of scarlet oak trees on the Tennessee Cumberland Plateau. Res. Pap. SE-214, U.S. Dep. Agric. For. Serv. 23 p.

Clark, A. III, D. R. Phillips, and H. C. Hitchcock III. 1980c. Predicted weights and volumes of southern red oak trees on the Highland Rim in Tennessee. Res. Pap. SE-208. U.S. Dep. Agric. For. Serv. 23 p.

Davis, R. E., Jr. 1973. The effect of rock type on the chemical composition of red oak and yellow poplar. (Abstr.) M. S. thesis. W. Va. Univ., Morgantown, W. Va.

El-osta, M. L. M. And R. W. Wellwood. 1972. Short-term creep as related to cell-wall crystallinity. Wood and Fiber 4:204-211.

Erickson, H. D. 1949. Relation of specific gravity to shrinkage and of these factors to growth in yellow poplar. J. Agric. Res. 78:103-127.

Ezell, A. W., and P. E. Schilling. 1980. A note on within-tree variation of specific gravity in sweetgum (*Liquidambar styraciflua* L.). Wood and Fiber 12:80-87.

Farmer, R. E., Jr. and W. L. Nance. 1969. Phenotypic variation in specific gravity and fiber length of cherrybark oak. Tappi 52:317-319.

Gilmore, A. R. 1971. Specific gravity of plantation-grown yellow-poplar is not related to site. Wood and Fiber 3:182-183.

Hamilton, J. R. 1961. Variation of wood properties in southern red oak. For. Prod. J. 11:267-271.

Hamilton, J. R., F. C. Cech, and C. E. Shurtliffe. 1976. Estimating bole specific gravity from limbs of mature black cherry and northern red oak trees. Wood and Fiber 7:281-286.

Harder, M. L. 1976. Pycnometer method for obtaining wood and bark chip densities. For. Sci. 22:191-192.

Heinrichs, J. F. 1954. Rapid specific gravity determinations. J. For. Prod. Res. Soc. 4:68.

Heinrichs, J. F. and L. E. Lassen. 1970. Improved technique for determining the volume of irregularly shaped wood blocks. For. Prod. J. 20(4):24.

Hunter, A. G. and J. F. Goggans. 1968. Variation in specific gravity, diameter growth, and colored heartwood of sweetgum in Alabama. Tappi 51:76-79.

Jett, J. B. and B. J. Zobel. 1975. Wood and pulping properties of young hardwoods. Tappi 58(1):92-96.

Johnson, J. W., and R. L. McElwee. 1967. Geographic variation in specific gravity and three fiber characteristics of sweetgum. Ninth South. Conf. For. Tree Improv. Proc., p. 50-55.

Julien, L. M., J. C. Edgar, and T. M. Conder. 1971. A density-gradient technique for obtaining wood and bark chip density. U.S. Dep. Agric. For. Serv., Res. Note NC-112. 4 p.

Kellison, R. C. 1967. A geographic variation study of yellow-poplar (*Liriodendron tulipifera* L.) within North Carolina. Tech. Rep. No. 33, 41 p. N. C. State Univ., Raleigh, N. C.

Kellison, R. C., and B. J. Zobel. 1971. Wood specific gravity and moisture content of five hardwood species of the southern United States. J. Ser. Pap. No. 3408, 13 p. Agric. Exp. Stn., N. C. State Univ., Raleigh.

Kellogg, R. M., C. B. R. Sastry and R. W. Wellwood. 1975. Relationships between cell-wall composition and cell-wall density. Wood and Fiber 7:170-177.

Kellogg, R. M. and F. F. Wangaard. 1969. Variation in the cell-wall density of wood. Wood and Fiber 1:180-204.

Koch, C. B., A. Brauner, and D. Kulow. 1968. Specific gravity variation within young yellow-poplar trees. West Va. Univ. Agric. Exp. Stn. Bull. 564T, 9 p.

Kollmann, F. F. P. and W. A. Côté, Jr. 1968. Principles of wood science and technology. I. Solid wood. 592 p. N. Y.: Springer-Verlag, New York Inc.

Luxford, R. F. and L. W. Wood. 1953. Survey of strength and related properties of yellow-poplar. U.S. Dep. Agric. For. Serv., For. Prod. Lab. Rep. No. 1610. 44 p.

Manwiller, F. G. 1972. Wood and bark properties of spruce pine. U.S. Dep. Agric. For. Serv., Res. Pap. SO-78. 25 p.

Manwiller, F. G. 1975. Wood and bark moisture contents of small-diameter hardwoods growing on southern pine sites. Wood Sci. 8:384-388.

Manwiller, F. G. 1979. Wood and bark specific gravity of small-diameter pine-site hardwoods in the South. Wood Sci. 11:234-240.

McElwee, R. L., R. C. Tobias, and A. H. Gregory. 1970. Wood characteristics of three southern hardwood species and their relationship to pulping properties. Tappi 53:1882-1886.

McGinnes, E. A., Jr. and R. A. Ralston. 1967. Growth-quality evaluation of black and scarlet oak grown in Missouri. Agric. Exp. Stn. Res. Bull. 912, 15 p. Univ. of Mo., Coll. of Agric., Columbia, Mo.

Morschauser, C. R. 1954. The effect of rays on the differential shrinkage of red oak. J. of For. Prod. Res. Soc. 4:280-282.

Müller-Stoll, W. R. 1948. Photometrische Holzstrukturuntersuchungen. II. Mitteilung: Über die Beziehungen der Lichtdurchlässigkeit von Holzschnitten zu Rohwichte und Wichtekontrast. Forstwiss. Centr. 68:21-63.

Murphey, W. K., W. J. Young, and B. E. Cutter. 1973. Effects of sewage effluent irrigation on various physical and anatomical characteristics of northern red oak. Wood Sci. 6:65-71.

Parker, M. L. and L. A. Pozsa. 1977. Use of the on-line computer-densitometer system to rapidly produce summary density profiles. *In* Bi-Monthly Res. Notes 33(2):13.

Paul, B. H. 1926. How growth affects quality in hickory and ash. Wood Work. Ind. 2(2):28-30.

Paul, B. H. 1929. The relation of rate of growth to the production of white wood in hickory trees. South. Lumberman 137(1765):67.

Paul, B. H. 1942. Variation in the porosity of twelve species of oak. South. Lumberman 164(2063):31-33.

Paul, B. H. 1960. How growth affects quality in hardwood lumber. South. Lumberman 201(2512):31-32.

Paul, B. H. 1962. Yellow-poplar—Past and future. South. Lumberman 204(2544):29-31.

Paul, B. H. 1963. The application of silviculture in controlling the specific gravity of wood. U.S. Dep. Agric. For. Serv., Tech. Bull. No. 1288. 97 p.

Paul, B. H. and M. E. Baudendistel. 1943. A field method of determining specific gravity by use of increment cores or auger chips. U.S. Dep. Agric. For. Serv., For. Prod. Lab. Rep. 1587. 7 p.

Paul, B. H. and R. O. Marts. 1934. Growth, specific gravity, and shrinkage of twelve delta hardwoods. J. of For. 32:861-873.

Paul, B. H. and N. A. Norton. 1936. Variations in the wood of yellow poplar from the southern Appalachian region. J. of For. 34:936-942.

Phillips, D. R. 1977. Total-tree weights and volumes for understory hardwoods. Tappi 60(6):68-71.

Phillips, D. R. and J. P. McClure. 1976. Composition, volume, and physical properties of the hardwood understory. Proc. fourth annu. hardwood symp. Hardwood Res. Counc., pp. 22-29.

Pillow, M. Y. 1939. Characteristics of ash from southern bottomlands. South. Lumberman 159(2009):131-136.

Pillow, M. Y. 1951. Selecting white oak trees for bending lumber. For. Prod. Res. Soc. Proc. 5:87-92.

Pillow, M. Y. 1950. Guides for selecting tough ash. South. Lumberman 181(2264):42, 46, 48, 50, 52.

Pronin, D. 1966. Methods for estimating specific gravity of logs. U.S. Dep. Agric. For. Serv., Res. Note FPL-0110. 9 p.

Roberds, J. H. 1965. Patterns of variation in several characteristics of sweetgum (*Liquidambar styraciflua* L.) in North Carolina. M. S. thesis. 62 p. N. C. State Univ., Raleigh, N. C.

Sachs, I. B., J. C. Ward, and E. H. Bulgrin. 1966. Heartwood stain in red oak. Holz als Roh- und Werkstoff 24:489-497.

Saucier, J. R. and M. A. Taras. 1966. Specific gravity and fiber length variation within annual height increments of red maple. For. Prod. J. 16(2):33-36.

Schroeder, J. G. and D. R. Phillips. 1973. Some physical properties of yellow-poplar wood and bark. Part II: variations with height in the tree. Wood Sci. 6:123-126.

Sluder, E. R. 1972. Variation in specific gravity of yellow-poplar in the southern Appalachians. Wood Sci. 5:132-138.

Smith, D. M. 1954. Maximum moisture content method for determining specific gravity of small wood samples. U.S. Dep. Agric. For. Serv., For. Prod. Lab. Rep. 2014. 8 p.

Smith, D. M. 1961. Method of determining specific gravity of wood chips. U.S. Dep. Agric. For. Serv., For. Prod. Lab. Rep. 2209, 8 p.

Smith, D. M. 1965. Rapid measurement of tracheid cross-sectional dimensions of conifers: its application to specific gravity determinations. For. Prod. J. 15:325-334.

Stamm, A. J. 1929. Density of wood substance, adsorption by wood, and permeabiliy of wood. J. Phys. Chem. 33:398-414.

Taras, M. A. and J. R. Saucier. 1968. Wood density surveys of the minor species of yellow pine in the eastern United States. Part I—Spruce pine (*Pinus glabra* Walt.) U.S. Dep. Agric. For. Serv., Res. Pap. SE-34. 15 p.

Taylor, F. W. 1964. Differences in the wood of yellow-poplar. For. Farmer 24(2):8-9, 19.

Taylor, F. W. 1965. A study of the natural variation of certain properties of the wood of yellow-poplar (*Liriodendron tulipifera*) within trees, between trees, and between geographic areas. Ph.D. thesis. N. C. State Univ., Raleigh, N. C. 190 p.

Taylor, F. W. 1968. Specific gravity differences within and among yellow-poplar trees. For. Prod. J. 18(3):75-81.

Taylor, F. W. 1969. The effect of ray tissue on the specific gravity of wood. Wood and Fiber 1:142-145.

Taylor, F. W. 1971. Variation of wood properties in sugarberry. For. Prod. Util. Lab. Res. Rep. No. 11, 17 p. State Coll., Miss.: Miss. State Univ.

Taylor, F. W. 1977a. Variation in specific gravity and fiber length of selected hardwoods throughout the Mid-South. For. Sci. 23:190-194.

Taylor, F. W. 1977b. A note on the relationship between branch- and stemwood properties of selected hardwoods growing in the Midsouth. Wood and Fiber 8:257-261.

Taylor, F. W. 1979. Property variation within stems of selected hardwoods growing in the Mid-South. Wood Sci. 11:193-199.

Thor, E., and H. A. Core. 1972. Relation of fertilization, irrigation and site factors with radial growth and wood properties of yellow-poplar. *In* Abst., Proc. Sixth TAPPI For. Biol. Conf., Inst. Pap. Chem., Appleton, Wis. Abst. V-1. 2 p.

Thorbjornsen, E. 1961. Variation in density and fiber length in wood of yellow poplar. Tappi 44:192-195.

Timson, F. G. 1975. Weight/volume ratios for Appalachian hardwoods. U.S. Dep. Agric. For. Serv., Res. Note NE-202. 2 p.

U.S. Department of Agriculture, Forest Service. 1956. Methods of determining the specific gravity of wood. U.S. Dep. Agric. For. Serv., For. Prod. Lab. Tech. Note B-14. 6 p.

U.S. Department of Agriculture, Forest Service. 1974. Wood handbook: Wood as an engineering material. U.S. Dep. Agric. For. Serv., Agric. Handb. 72, rev. For. Prod. Lab., Madison, Wis.

Wangaard, F. F. 1969. Cell-wall density of wood with particular reference to the southern pines. Wood Sci. 1:222-226.

Webb, C. D. 1964. Natural variation in specific gravity, fiber length and interlocked grain of sweetgum (*Liquidambar styraciflua* L.) within trees, among trees, and among geographic areas in the South Atlantic States. Ph.D. thesis. N. C. State Univ., Raleigh. 125 p.

Webb, C. D. 1965. Variation in the wood of sweetgum. For. Farmer 24(12):9, 16-18.

Wilfong, J. G. 1966. Specific gravity of wood substance. For. Prod. J. 16(1):55-61.

Winstead, J. E. 1972. Fiber tracheid length and wood specific gravity of seedlings as ecotypic characters in *Liquidambar styraciflua* L. Ecol. 53(1):165-172.

Wooten, T. E., T. W. Haene, and F. W. Taylor. 1973. Effect of tree release on wood quality of mature yellow-poplar trees. Wood Sci. 6:146-150.

Yakub, M. 1971. Variation in structure and specific gravity of yellow poplar (*Liriodendron tulipifera* L.). Forestdale News 4(1):26-31.

8

Wood-water relationships

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Subsection WOOD ANATOMY AND PERMEABILITY of section 8-6 is based on a paper by R.J. Thomas.

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CHAPTER 8

Wood-water relationships

Stemwood of living hardwood species on southern pine sites contains 0.5 to 1.2 pounds of water for each pound of dry wood depending on species; when weighted by species' volume on pine sites, the average water content of stemwood of these trees is about 0.85 pound of water per pound of dry wood. In use, wood generally serves best if most of this water is removed because many of the desirable properties of wood are negatively correlated with its moisture content and because dry wood is less subject to decay than moist wood. Some utilization processes require that water solutions of various chemicals be made to penetrate wood. For these reasons, it is desirable to know the location of water in wood and the manner of its movement.

Moisture content is usually expressed as a percentage of the ovendry weight of wood.

Percentage moisture content

$$= \frac{\text{(weight of wood with moisture—ovendry weight of wood)}}{\text{ovendry weight of wood}}(100) \qquad (8\text{-}1)$$

The ovendry weight of wood is measured after drying it to a constant weight in an oven held at 101° to 105°C.

There are numerous methods of measuring and computing moisture content. The interested reader will find techniques described in the following references.

Ovendrying	American Society for Testing and Materials (1974, p. 581) Browning (1967, p. 61) Skaar (1972, p. 32)
Vacuum drying	Browning (1967, p. 62) Loos and Robinson (1968) Skaar (1972, p. 33)
Distillation	American Society for Testing and Materials (1974, p. 586) Browning (1967, p. 62) Skaar (1972, p. 33)
Karl Fischer titration	Browning (1967, p. 65) Loos and Robinson (1968) Skaar (1972, p. 34)
Electric moisture meter	American Society for Testing and Materials (1974, p. 583) Hejjas and Salamon (1977) James (1963, 1965, 1968, 1975ab) Mackay (1976) Preikschat et al. (1974) Skaar (1964)

Probe	Duff (1966)
	Hill and Munkittrick (1970)
Electric hygrometer	American Society for Testing and Materials (1974, p. 588)
Microwave absorption	Busker (1968)
	Lowery and Kotok (1967)
	Lundstrom (1970)
Nuclear magnetic resonance	Bersenev et al. (1963)
	Nanassy (1973, 1974, 1976)
	Swanson et al. (1962)
	Wall (1958)
Nuclear radiation	Gibson and Rusten (1964)
	Kajanne and Hollming (1958)
	Loos (1961, 1965)
	Skaar (1972, p. 53)
Infrared backscatter gage	Beutler (1965)

8-1 MOISTURE CONTENT IN LIVING TREES

The water content of wood in hardwoods varies among species, within species, and within trees.

VARIATION AMONG SPECIES

Because of the size and continuously changing nature of the populations, it is difficult to obtain data that truly represent tree-average values of wood moisture content for each species. Table 8-1 lists moisture content data accumulated by the U.S. Forest Products Laboratory over many years; values, which are averages for merchantable trees generally 12-inches and greater dbh over all sites, range from a low of 44 percent in sapwood of white ash to a high of 137 percent in sapwood of sweetgum.

Table 8-1A shows the moisture content of components of seven species of southern hardwood trees 6 to 22 inches in diameter sampled in various regions of North Carolina, Tennessee, and Georgia.

TABLE 8-1.—*Moisture content in sawlog-size stemwood of 14 hardwoods commonly associated with southern pines* (U.S. Department of Agriculture, Forest Service 1974, p. 3-3)

Species	Moisture content[1]	
	Heartwood •	Sapwood
Ash, green	—	58
Ash, white	46	44
Elm, American	95	92
Hackberry	61	65
Hickory, bitternut	80	54
Hickory, mockernut	70	52
Hickory, pignut	71	49
Oak, northern red	80	69
Oak, southern red	83	75
Oak, water	81	81
Oak, white	64	78
Sweetgum	79	137
Tupelo, black	87	115
Yellow-poplar	83[2]	106

[1] Based on weight when ovendry.

[2] Phillips and Schroeder (1973) found that heartwood of 50-year-oid yellow-poplar sampled in the southern Appalachian Mountains near Brevard, North Carolina, had average moisture content of about 97 percent.

TABLE 8–1A.—*Moisture content[1] of wood and bark of components of seven species of southern hardwood trees 6 to 22 inches in diameter* (Clark and Schroeder 1977; Clark et al. 1980abc; and personal communication with J. G. Schroeder, A. Clark III, and D. R. Phillips November 1981)[2]

Tree component	Wood	Bark
	Percent	
CHESTNUT OAK FROM MOUNTAINS OF WESTERN NORTH CAROLINA		
Whole tree[3]	69 ± 3.0	61 ± 6.6
Stem (butt to 4-inch dib top)	70 ± 3.6	57 ± 7.0
Sawlog (butt to 8-inch dib top)	71 ± 4.0	59 ± 6.7
Pulpwood (8- to 4-inch dib top)	66 ± 4.2	54 ± 6.8
Topwood (4- to 2-inch dib top)	64 ± 3.4	57 ± 9.9
Branches	63 ± 2.9	74 ± 10.9
NORTHERN RED OAK FROM WESTERN NORTH CAROLINA		
Whole tree	80 ± 4.9	63 ± 5.8
Stem (butt to 4-inch dib top)	83 ± 5.4	61 ± 6.1
Sawlog (butt to 8-inch dib top)	85 ± 5.8	58 ± 6.0
Pulpwood (8- to 4-inch dib top)	72 ± 4.7	55 ± 5.6
Branches	69 ± 4.0	66 ± 9.0

See footnotes at the end of table.

TABLE 8–1A.—*Moisture content*[1] *of wood and bark of components of seven species of southern hardwood trees 6 to 22 inches in diameter* (Clark and Schroeder 1977; Clark et al. 1980abc; and personal communication with J. G. Schroeder, A. Clark III, and D. R. Phillips November 1981)[2]—Continued

Tree component	Wood	Bark
	Percent	
SCARLET OAK FROM TENNESSEE CUMBERLAND PLATEAU		
Whole tree	76 ± 4.4	59 ± 3.1
Stem (butt to 4-inch dib top)	80 ± 5.4	57 ± 4.0
Sawlog (butt to 8-inch dib top)	83 ± 5.1	58 ± 4.6
Pulpwood (8- to 4-inch dib top)	67 ± 4.8	56 ± 3.5
Topwood (4- to 2-inch dib top)	68 ± 4.8	58 ± 5.6
Branches	62 ± 3.2	62 ± 5.9
SOUTHERN RED OAK FROM HIGHLAND RIM OF TENNESSEE		
Whole tree	74 ± 5.8	47 ± 4.7
Stem (butt to 4-inch dib top)	79 ± 7.0	44 ± 3.9
Sawlog (butt to 8-inch dib top)	81 ± 6.6	44 ± 4.3
Pulpwood (8- to 4-inch dib top)	72 ± 4.8	43 ± 4.0
Topwood (4- to 2-inch dib top)	65 ± 3.7	48 ± 7.0
Branches	60 ± 4.2	55 ± 5.1
WHITE OAK FROM WESTERN NORTH CAROLINA		
Whole tree	70 ± 5.4	73 ± 6.3
Stem (butt to 4-inch dib top)	72 ± 7.0	66 ± 6.9
Sawlog (butt to 8-inch dib top)	74 ± 7.0	67 ± 7.7
Pulpwood (8- to 4-inch dib top)	66 ± 4.2	64 ± 7.3
Topwood (4- to 2-inch dib top)	63 ± 4.4	67 ± 6.3
Branches	63 ± 3.9	84 ± 9.9
SWEETGUM FROM THE GEORGIA PIEDMONT		
Whole tree	116 ± 11.7	91 ± 12.6
Stem (butt to 4-inch dib top)	119 ± 11.8	79 ± 12.7
Sawlog (butt to 8-inch dib top)	116 ± 12.6	75 ± 11.9
Pulpwood (8- to 4-inch dib top)	114 ± 14.3	81 ± 11.4
Topwood (4- to 2-inch dib top)	106 ± 15.1	96 ± 14.6
Branches	100 ± 10.6	125 ± 23.2
YELLOW-POPLAR FROM WESTERN NORTH CAROLINA		
Whole tree	104 ± 13	142 ± 36
Stem (butt to 4-inch dib top)	104 ± 14	126 ± 29
Sawlog (butt to 8-inch dib top)	103 ± 13	124 ± 28
Pulpwood (8- to 4-inch dib top)	103 ± 18	123 ± 35
Topwood (4- to 2-inch dib top)	111 ± 13	151 ± 27
Branches	106 ± 15	247 ± 66

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[1] Based on ovendry weight.

[2] Values are based on 24 to 36 trees of each species.

[3] Foliage-free, above-ground portions.

Because hardwoods on southern pine sites are typically small in diameter, species average values specific to 6-inch trees from such sites should be useful to readers of this text; moisture content of stemwood from these pine-site hardwoods ranges from a low of 47.4 percent in green ash to a high of 120.4 percent in sweetgum (table 8-2). Branchwood moisture ranges from 46.1 percent (white ash) to 108.8 percent (sweetgum).

The small number of trees of each species sampled (10) leaves the possibility of some error in estimating South-wide means. In any event, the average value for a particular locality may well deviate considerably from the South-wide mean. Despite such limitations, the values in table 8-2 provide the best information currently available on moisture content of hardwoods growing on southern pine sites.

These among-species variations are to some degree rationalized as a function of specific gravity; in general, percent moisture content and specific gravity of stemwood are inversely correlated (fig. 8-1). Ash species are exceptional in that they have very low wood moisture content in spite of their intermediate density.

Because much of the hardwood volume on southern pine sites is in trees 1 to 5 inches in diameter, data for seven species of such trees are shown in table 7-8. Yellow-poplar and sweetgum had highest moisture content for wood and bark (122 to 141 percent), hickory had lowest (58 to 66 percent) and the other four species were intermediate (68 to 96 percent). Understory trees of these species growing in the Piedmont of South Carolina are described on page 1176.

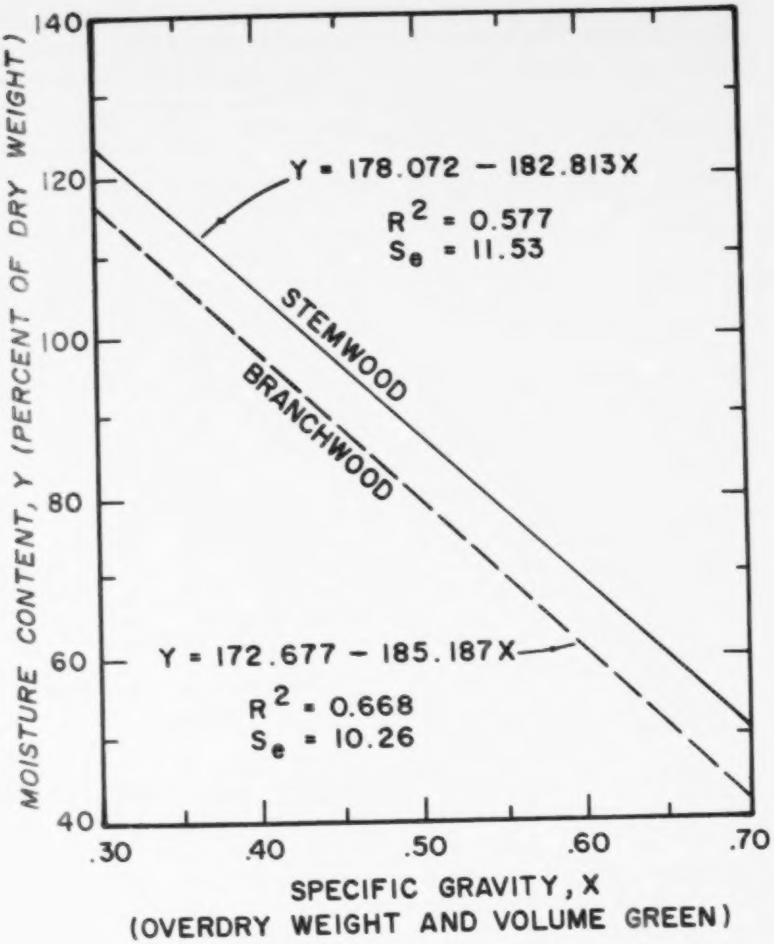

Figure 8-1.—Relation of percent moisture content when green to specific gravity in stemwood and branchwood of 22 species of 6-inch hardwoods sampled Southwide from southern pine sites. The regressions are based on a 10-tree sample of each species. (Data from tables 7-7 and 8-2).

TABLE 8–2.—*Moisture content*[1] *(with standard deviation in parentheses) of 6-inch hardwoods growing on southern pine sites* (Manwiller 1975)

Species	Stem wood	Stem bark	Stem	Branch wood	Branch bark	Branch	Tree
	Percent						
Ash, green	47.4	75.9	51.4	46.9	86.0	55.6	51.9
	(3.9)	(8.6)	(4.2)	(3.7)	(10.2)	(3.9)	(4.2)
Ash, white	47.5	68.4	50.5	46.1	77.9	54.7	51.0
	(3.1)	(11.4)	(3.3)	(4.1)	(8.6)	(4.3)	(3.2)
Elm, American	75.5	86.9	76.8	64.9	97.8	71.9	76.3
	(7.5)	(7.7)	(6.4)	(7.6)	(6.8)	(5.8)	(6.4)
Elm, winged	65.6	76.0	66.7	61.0	79.5	65.3	66.5
	(5.3)	(7.8)	(4.9)	(6.3)	(7.8)	(5.2)	(4.9)
Hackberry[2]	72.6	55.5	70.5	64.0	71.7	65.4	69.8
	(6.3)	(6.1)	(5.9)	(7.6)	(8.7)	(7.0)	(6.1)
Hickory	51.5	72.9	55.6	48.4	84.6	57.1	55.7
	(3.0)	(10.5)	(3.9)	(4.0)	(10.8)	(3.8)	(3.9)
Maple, red	69.9	74.4	70.5	73.7	89.4	77.1	71.5
	(2.9)	(2.6)	(2.5)	(4.9)	(6.9)	(4.6)	(2.3)
Oak, black	69.2	56.2	66.2	55.7	62.5	57.3	65.1
	(4.8)	(5.4)	(4.3)	(4.1)	(4.0)	(3.2)	(4.2)
Oak, blackjack	74.2	43.6	65.6	59.2	56.2	57.9	64.4
	(5.3)	(6.4)	(3.8)	(5.1)	(8.9)	(3.6)	(3.8)
Oak, cherrybark	66.6	54.1	64.3	55.9	68.2	58.5	63.7
	(6.3)	(4.2)	(4.8)	(4.3)	(3.6)	(3.9)	(4.6)
Oak, chestnut	—	—	—	—	—	—	—
Oak, laurel	74.4	57.4	71.9	61.4	76.0	64.2	70.9
	(5.2)	(6.3)	(5.0)	(3.9)	(6.6)	(3.7)	(5.0)
Oak, northern red	69.7	55.7	66.8	59.2	62.6	60.2	66.0
	(8.1)	(14.5)	(8.0)	(7.2)	(5.6)	(6.4)	(7.6)
Oak, post	65.6	48.9	62.0	60.7	65.1	61.9	62.0
	(6.0)	(9.4)	(5.8)	(6.7)	(12.0)	(7.7)	(6.0)
Oak, scarlet	69.4	55.6	66.6	53.6	67.0	57.0	65.6
	(5.1)	(8.6)	(5.7)	(3.4)	(7.7)	(4.2)	(5.9)
Oak, Shumard	69.1	52.2	66.2	55.4	66.1	57.8	65.4
	(5.8)	(4.0)	(5.3)	(5.4)	(5.9)	(4.9)	(5.1)
Oak, southern red	70.1	52.9	66.0	57.5	66.6	59.7	65.2
	(4.3)	(8.1)	(5.2)	(2.8)	(6.1)	(3.3)	(4.9)
Oak, water	73.6	54.4	70.1	63.5	73.5	65.5	69.7
	(7.4)	(7.0)	(6.5)	(6.1)	(8.1)	(6.0)	(6.4)
Oak, white	61.9	58.1	61.4	58.1	69.6	61.0	61.3
	(5.0)	(8.5)	(5.1)	(4.5)	(8.8)	(4.8)	(4.9)
Sweetbay	100.8	102.1	101.2	99.4	100.6	99.9	101.2
	(6.6)	(11.6)	(6.5)	(13.1)	(13.0)	(11.7)	(7.0)
Sweetgum	120.4	89.3	116.0	108.8	106.9	108.5	115.3
	(12.0)	(9.9)	(10.6)	(5.3)	(8.2)	(3.3)	(9.7)
Tupelo, black	90.0	69.8	85.7	89.8	88.4	89.0	85.9
	(9.7)	(16.9)	(8.0)	(10.5)	(12.8)	(9.9)	(7.9)
Yellow-poplar	111.7	125.8	113.4	105.3	134.4	111.6	113.4
	(9.7)	(23.9)	(8.2)	(8.6)	(14.3)	(5.8)	(7.7)

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[1] Based on weight when ovendry; each value is an average of 10 trees. See tables 3-1 and 16-3 for additional tree data. Values tabulated here correct minor errors in source document.

[2] Mostly sugarberry.

Wartluft (1977) has provided information on moisture content of above-ground portions (excluding foliage) of entire small trees (1- to 10-inch dbh) sampled from a single stand in the Monongahela National Forest of West Virginia, as follows:

Species	Trees sampled	Moisture content
	Number	*Percent of dry weight*
Hickory	13	54
Maple, red	47	69
Oak, chestnut	32	64
Oak, red (several species)	31	75
Oak, white	28	66
Tupelo, black	4	89
Yellow-poplar	4	104

Hitchcock (1978) found that very small Tennessee hardwoods (dbh 1.7 to 3.0 cm) cut in winter months when leaves were absent had weighted average moisture content in above-ground portions as follows; data are based on 20 trees of each species.

Species	dbh	Weighted moisture content
	cm	*Percent of dry weight*
Hickory	2.5	69
Maple, red	2.2	79
Oak, chestnut	1.8	73
Oak, red (several species)	2.6	60
Oak, white	3.0	67
Tupelo, black	1.7	100
Yellow-poplar	2.2	102

WITHIN-SPECIES VARIATIONS

Moisture content in living trees of hardwood species may vary with tree specific gravity, age, geographic location, genetic background, and possibly with season of the year. In combination, these factors contribute to a substantial range in tree-average moisture contents. Among 6-inch trees, standard deviations for stemwood percent moisture content ranged from 2.9 for red maple to 12.0 for sweetgum; for branchwood, standard deviations of 2.8 (southern red oak) to 13.1 (sweetbay) were observed (table 8-2).

Additional data on standard deviations of moisture content among yellow-poplar trees has been provided by Clark and Schroeder (1977) as follows:

Tree component	Moisture content (and standard deviation)	
	Wood	Bark
	Percent of ovendry weight	
Total tree	104 (13)	142 (36)
Total stem	104 (14)	126 (24)
Sawlog section	103 (13)	124 (28)
Pulpwood section	103 (18)	123 (35)
Topwood section	111 (13)	151 (27)
Branches	106 (15)	247 (66)

These data are based on 39 trees from two natural, closed, uneven-aged mountain cove stands of yellow-poplar in western North Carolina, one of pulpwood size, the other mainly sawtimber.

Sapwood and bark from logs sampled by Choong and Cassens (1976) at two Louisiana sawmills both varied widely in moisture content as follows (each average value represents data from 9 to 22 logs):

Species and location	Moisture content (and standard deviation)	
	Sapwood	Bark
Ash species		
Plaquemine	69.9 (14.3)	62.7 (7.2)
Alexandria	46.3 (5.9)	39.9 (8.7)
Elm species		
Plaquemine	140.9 (35.1)	85.2 (14.2)
Red oak species		
Plaquemine	90.7 (22.5)	64.0 (21.6)
Alexandria	74.2 (12.9)	45.1 (11.1)
White oak species		
Plaquemine	98.7 (14.4)	70.7 (13.4)
Sweetgum		
Plaquemine	141.2 (28.7)	(63.8) (9.6)
Alexandria	104.0 (22.0)	49.6 (9.2)

In trees aged 20 to 60 years sampled throughout the Southeast, Kellison and Zobel (1971) found great variation among trees in stemwood moisture content, as follows (each average value represents 59 to 76 trees):

Species	Moisture content	
	Tree average	Range
	Percent of dry weight	
Ash, green	51	41-68
Maple, red	73	55-100
Oak, water and willow	78	68-95
Sweetgum	121	98-145

No common pattern associating these variations of moisture content **with site** was discernible. For example, sweetgum had highest moisture content on upland slopes (132 percent) while in muck swamps it averaged only 105 percent moisture; in red maple moisture content was lowest on upland slopes (59 percent), and highest in Red River bottoms (76 percent).

In the Kellison-Zobel (1971) study moisture contents of trees differed considerably among areas, but differences did not appear to have **geographical trends.** Henderson and Choong (1968) found only minor moisture variations in sweetgum stemwood among Louisiana locations; differences in moisture content among hilltop, slope, and bottomland sites were not significant.

Jett and Zobel (1975) reported variations among young trees of a magnitude comparable to those in mature trees, as follows:

Species	Tree age	Stemwood moisture content	
		Average	Range
	Years	*Percent of dry weight*	
Ash	2	54	44-74
Sweetgum	6	137	123-147

Data on average moisture content of stemwood related to **age class** of trees is scarce. Wartluft's (1977) study of 200 West Virginia trees of 17 hardwood species 1 to 10 inches dbh, found average green-wood moisture content of about 70 percent, but no correlation between and moisture content and diameter. Bark moisture content, however, was greatest (95-percent) in 1-inch and least (60-percent) in 8-inch trees.

Kellison and Zobel's (1971) information on 8- and 9-inch diameter green ash 20 to 60 years old also indicates little correlation between age and stemwood moisture content, as follow:

Tree age class	Stemwood moisture content
Years	*Percent*
20	48
30	53
40	50
50	50
60	49

Jett and Zobel (1975), however, indicated that sweetgum trees 2 to 6 years old had wood of higher moisture content than trees 10 to 15 years old, as follows:

Tree age	Moisture content
Years	*Percent*
2	134
6	137
10	119
15 +	121

Variation of wood moisture content with **season of the year** apparently differs with species. Yellow-poplar wood moisture content does not vary significantly with season of the year at any position in the tree (Phillips and Schroeder 1973).

Henderson and Choong (1968) reported a significant difference in the seasonal moisture content of stemwood of sweetgum in Louisiana. The high moisture content was reported in July (121 percent) and the low in October (93 percent). In their study, tree moisture content values were determined from 4.5 mm increment cores extracted at breast height rather than from disks taken at intervals along the stem. They also reported significant two- and three-factor interactions between seasons, sites, and locations. These interactions would preclude a general statement about any of the main effects, so that each statement about seasonal moisture fluctuation must be qualified as to which site and location it represents.

Supporting the concept that stemwood of hardwoods varies little in moisture content throughout the year, are data from near Clemson, South Carolina reported (fig. 8-2) by Smith and Goebel (1952). In their sample trees, heartwood moisture content was higher and somewhat more variable than that of sapwood.

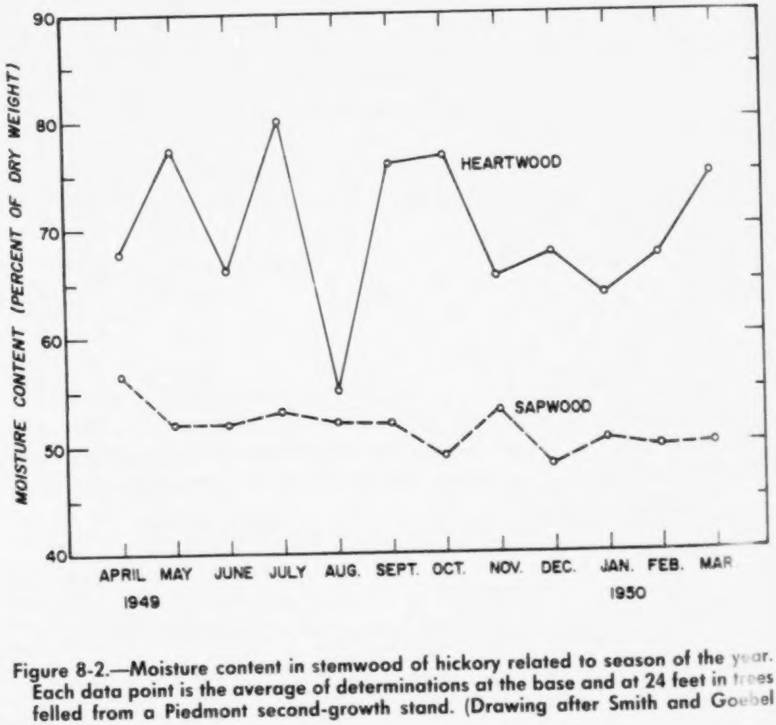

Figure 8-2.—Moisture content in stemwood of hickory related to season of the year. Each data point is the average of determinations at the base and at 24 feet in trees felled from a Piedmont second-growth stand. (Drawing after Smith and Goebel 1952.)

Although not one of the species under consideration, Clark's (1975) data on 4-year-old coppice sycamore (*Platanus occidentalis* L.) is useful in understanding moisture content variation with season. Stem moisture content (wood plus bark) was near 160 percent from July to late August, declining to a low of 139 percent in mid-October (fig. 8-3). After a secondary high of 152 percent in December and a secondary low of 142 percent in mid-April, it again increased to near 160 percent as new foliage developed. The bark content of these young trees may have obscured trends in stemwood moisture content, because bark of some species varies significantly in moisture content with season (see chapter 13). Moisture content of the live branches (wood and bark) followed the same general pattern but varied more widely. Dead branches varied in moisture content from 16 to 38 percent, probably in response to varying atmospheric conditions, but showed no distinct seasonal pattern.

WITHIN-TREE VARIATION

Moisture content in stemwood of hardwoods varies with radial position in the stem including differences between heartwood and sapwood, and with height above the ground. Additionally, branchwood has moisture content different from stemwood. These variations make it difficult to uniformly dry some hardwoods.

Radial variation.—Available data on radial variation of moisture content in stemwood of southern hardwoods are expressed as differences between heartwood and sapwood. Heartwood has lower moisture content than sapwood in five of the 13 species described in table 8-1 (hackberry, white oak, sweetgum, black tupelo, and yellow-poplar). In water oak, heartwood and sapwood have the same moisture content (81 percent). In seven of the species (white ash—and probably green ash, American elm, bitternut hickory, mockernut hickory, pignut hickory, northern red oak, and southern red oak) heartwood has higher moisture content than sapwood.

This variability in heartwood moisture content of the various species is not readily explained. In *populus* species, and in some others, abnormally wet heartwood is attributable to activity of anaerobic bacteria; such infested wetwood is neutral or alkaline in Ph, fetid in odor, and contains methane under pressure (Ward and Zeikus 1974, Sachs et al. 1974). For most hardwoods on pine sites, however, high moisture content in heartwood is probably not due to bacteria.

Stemwood and branchwood.—Of the 22 species for which data are available on 6-inch trees (table 8-2), only red maple has branchwood of higher moisture content (75.1 percent) than that of its stemwood (69.9 percent). In the other 21 species, stemwood has higher moisture content than branchwood. In blackjack, black, southern red, Shumard, and scarlet oaks, stemwood has 13 to 15 percentage points more moisture content than branchwood; for these species, stemwood averages 70.4 percent and branchwood 56.6 percent moisture.

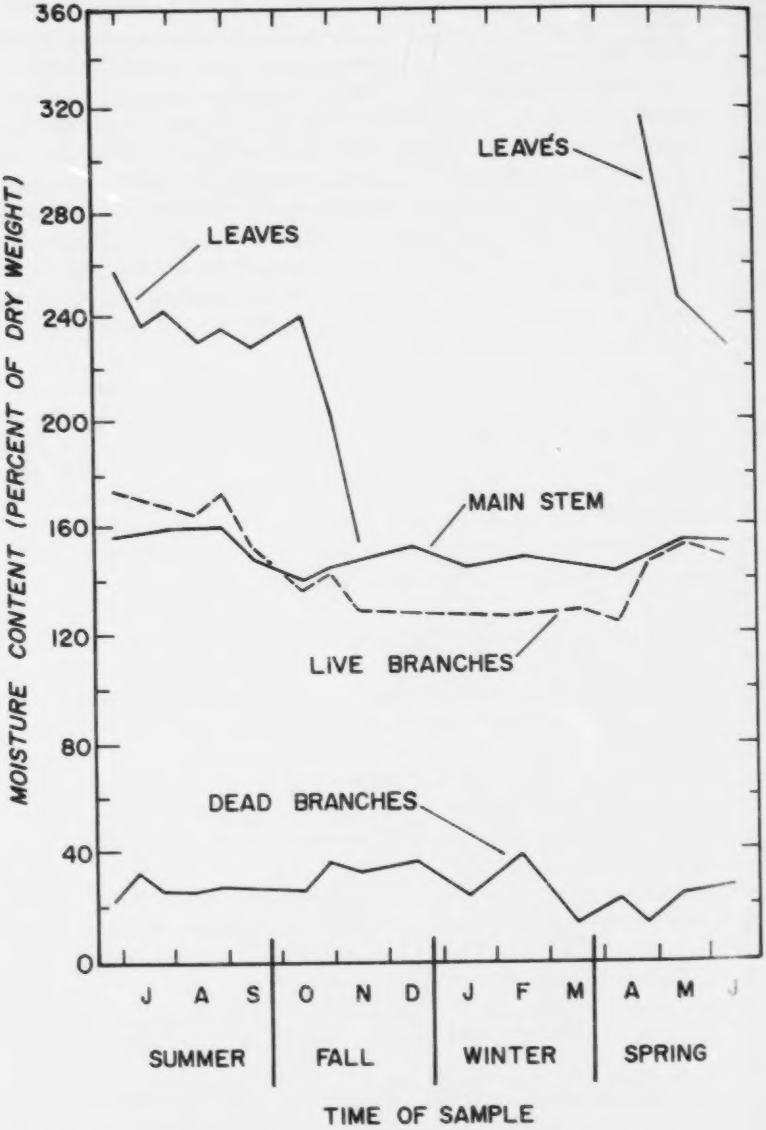

Figure 8-3.—Seasonal variation in moisture content of the above-ground biomass components of 4-year-old coppice sycamore. (Drawing after Clark 1975.)

Clark and Schroeder (1977) found that branchwood of yellow-poplar of all sizes had an average moisture content of 106 percent, while that of stemwood was 103 percent in the sawlog section and 111 percent in the topwood section; moisture content of branchbark was 247 percent, while stembark averaged 126 percent.

Phillips' (1977) study of understory hardwoods averaging about 3.0 inches in diameter showed moisture contents in stem and branches (wood and bark combined) as follows:

Species	North Carolina mountains		Georgia Piedmont	
	Stem	Branches	Stem	Branches
	Percent			
Yellow-poplar	132	128	141	134
Sweetgum	—	—	122	124
Red maple	89	96	80	80
White oak	68	74	73	71
Southern red oak	—	—	70	69
Chestnut oak	69	74	—	—
Hickory sp.	58	64	60	66

Variation with height in stem.—Data on variation of moisture content with height in stem are scarce. Kellison and Zobel (1971) concluded that in five hardwood species, a breast-height sample closely approximates tree-average moisture content of stemwood; their data follow:

Species	Moisture content	
	Breast-height disk	Weighted tree stemwood
	Percent of dry weight	
Ash, green	52	51
Maple, red	70	73
Oak, water and willow	79	78
Sweetgum	121	121
Sycamore	105	110

In hickory, sapwood has slightly lower moisture content at upper stem than at butt sections; heartwood, however, varies little with height in stem as follows (Smith and Goebel 1952):

Position in tree	Moisture content	
	Sapwood	Heartwood
	Percent of dry weight	
Butt	52.9	71.0
Upper portions	48.5	69.6

In yellow-poplar, moisture content of both heartwood and sapwood decrease significantly with height in tree; heartwood varies more widely than sapwood (fig. 8-4).

Data on the remaining species are absent. Since moisture content tends to vary inversely with stemwood specific gravity, moisture content trends should approximate the inverse of trends in specific gravity presented in chapter 7.

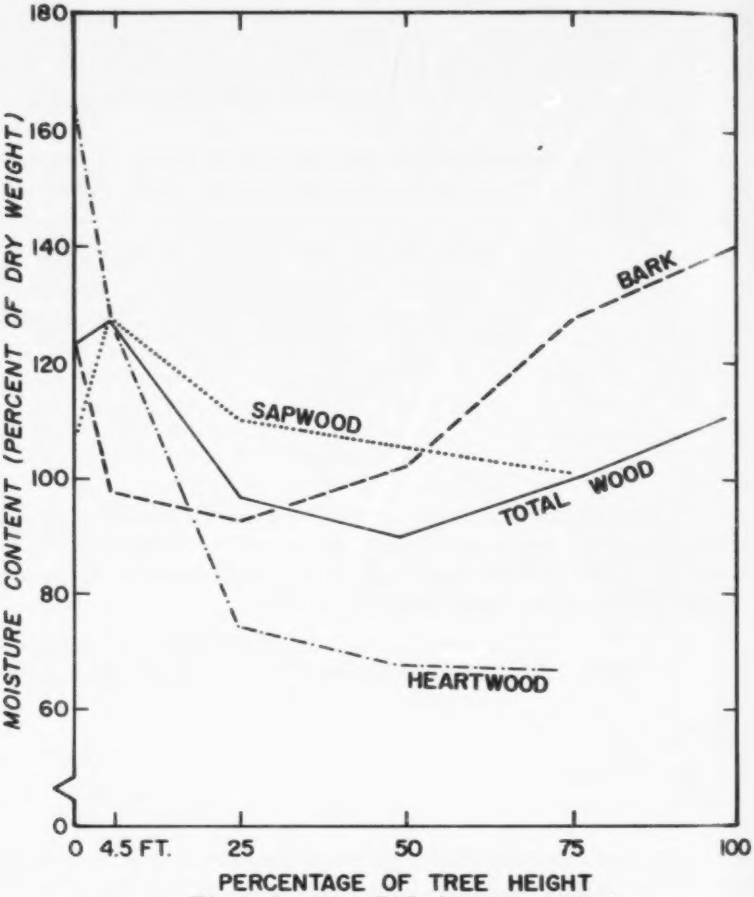

Figure 8-4.—Variation in the moisture content of yellow-poplar wood and bark with height in tree. Data are based on 60 trees, with breast-height diameters ranging from 9.6 to 10.5 inches, cut in the mountains of western North Carolina. (Drawing after Schroeder and Phillips 1973.)

MOISTURE CONTENT OF MILL RESIDUES

Mixed sawdust and bark from six hardwood sawmills in the area of Baton Rouge, Louisiana, had an average moisture content when fresh of 107 percent of dry weight; after extended storage in piles exposed to rainfall, moisture content averaged 184 percent (table 8-3). Rainfall in the Baton Rouge area averages about 62 inches annually, which probably accounts for the increase.

TABLE 8-3.—*Moisture content, green density, and heat of combustion per ovendry pound of fresh and piled sawdust and bark from hardwood sawmills near Baton Rouge, Louisiana* (Data from Cassens and Choong 1975)

Residue age and statistic	Heat of combustion	Moisture content[1]	Green density
	BTU/O.D. pound	*Percent*	*Pounds/cubic foot*
Fresh			
Average	8,017	107	24.0
Range	7,891-8,228	69-165	20.8-26.9
Piled			
Average	8,046	184	29.4
Range	7,815-8,862	88-380	22.5-38.1

[1] Basis of ovendry weight

8-2 FIBER SATURATION POINT

Wood is a **hygroscopic** material; it readily takes up and retains moisture when exposed to water vapor or liquid water. It holds water in three ways. **Water vapor** is present in the air within cell lumens, **free water** (sometimes termed capillary water) may be enclosed as a liquid within the lumens, and **bound water** is adsorbed by the cell wall polymers. Water vapor and free water do not form close associations with the wood substance. Bound water, however, is more closely bonded to the cell wall structure; three mechanisms are noted by Wangaard and Granados (1967, p. 255) in their review of the concept of adsorption.

- Formation of a monolayer of water molecules (Langmuir sorption) held by hydrogen bonds at polar sites on molecular surfaces in the noncrystalline regions of the cell wall. **Monomolecular adsorption** predominates at low relative humidities.
- Attraction of polymolecular water held in solid solution or as multilayers on the first-formed monolayer. **Polymolecular adsorption** predominates in the intermediate and higher ranges of relative humidity.
- **Capillary condensation** (expressed by the Kelvin equation relating the condensation of water vapor to relative vapor pressure and capillary size). The extent of capillary condensation is limited by volume of voids in the cell wall. As noted in section 7-2 the maximum void may be approximately 4 percent of the dry wall volume.

Sorption theories have also been reviewed by McLaren and Rowen (1951), King (1960), Morton and Hearle (1962), Barrie (1968), Venkateswaran (1970) and Skaar (1972).

As wet wood dries, free water leaves the lumens before bound water. The moisture content at which the cell walls are still saturated but no free water remains in the cell cavities is defined as the **fiber saturation** point (Tiemann 1906, p.82). As wood dries from its natural green moisture content, it does not commence to shrink until the fiber saturation point is reached. The fiber saturation point is also critical to most strength properties; above it they are constant, below it they are negatively correlated with moisture content.

While 30 percent is commonly accepted as the fiber saturation point of wood, values vary considerably between and within species (Spalt 1958). The variation is caused by differences in chemical composition, crystallinity of the cellulose, compactness of the cell wall, specific gravity, and extractive content. Values determined may also vary according to the experimental procedure used. Stamm (1971) reviewed nine such methods, including extrapolation to 100-percent relative humidity of sorption data on equilibrium moisture content, observation of shrinkage initiation with loss of moisture, correlation of strength or electrical properties with moisture content, or analysis by the polymer exclusion technique. Figure 8-5 illustrates determinations from shrinkage data.

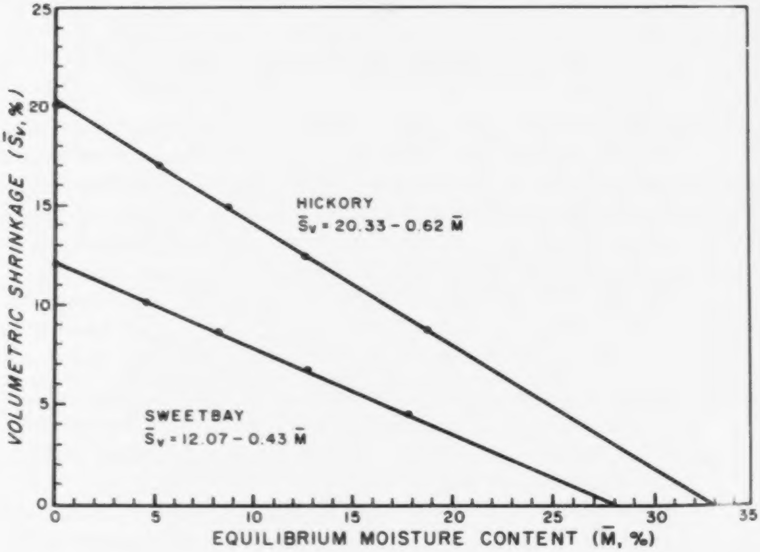

Figure 8-5.—Volumetric shrinkage as a function of equilibrium moisture content in hickory (R = −1.000) and sweetbay (R = −0.998); fiber saturation point is at intersection of regression line with zero shrinkage. (Drawing after Choong and Manwiller 1976.)

For the species that are the subject of this text, Okoh (1976) reported values based on extrapolation to 100-percent relative humidity of sorption data on equilibrium moisture content, and Choong and Manwiller (1976) derived comparable values from shrinkage initiation (table 8-4). Both sets of data are based on wood from identical trees, so results should reflect differences due to the two techniques.

Values for fiber saturation point based on adsorption data averaged 25.9 percent and ranged from 24.6 percent (white oak) to 29.1 percent (sweetgum); those based on desorption data averaged somewhat higher (28.6 percent) and ranged from 26.6 percent (red maple) to 32.7 percent (sweetgum). Fiber saturation point, based on both adsorption and desorption data for all species evaluated, averaged 27.3 percent.

Values based on initiation of shrinkage ranged from a low of 27.8 percent for winged elm to a high of 33.1 percent for white oak; the average was 30.4.

TABLE 8-4.—*Fiber saturation points determined by two methods for stemwood of 6-inch trees of 22 species of hardwood grown on southern pine sites*

Species	From sorption data[1] Adsorption	Desorption	Average	From shrinkage data[2]
	Percent of dry weight			
Ash, green	26.1	26.6	26.4	28.1
Ash, white	26.3	29.5	27.9	29.0
Elm, American	25.6	27.7	26.7	30.7
Elm, winged	26.4	29.4	27.9	27.8
Hackberry[3]	27.1	30.4	28.8	29.4
Hickory	26.9	29.5	28.2	32.9
Maple, red	24.9	27.6	26.3	28.9
Oak, black	24.8	27.0	25.9	31.3
Oak, blackjack	25.8	27.5	26.7	28.9
Oak, cherrybark	25.7	28.5	27.1	31.2
Oak, laurel	25.8	29.3	27.6	29.7
Oak, northern red	25.0	28.8	26.9	30.2
Oak, post	25.6	27.8	26.7	33.0
Oak, scarlet	25.4	27.6	26.5	30.5
Oak, Shumard	25.4	29.0	27.2	29.2
Oak, southern red	25.5	28.5	27.0	31.8
Oak, water	25.2	26.9	26.1	30.4
Oak, white	24.6	29.9	27.3	33.1
Sweetbay	25.9	27.3	26.6	28.1
Sweetgum	29.1	32.7	30.9	32.6
Tupelo, black	—	—	—	31.2
Yellow-poplar	26.4	29.0	27.7	30.6
Average	25.9	28.6	27.3	30.4

[1] Data from Okoh 1976

[2] Data from Choong and Manwiller 1976

[3] Mostly sugarberry

Never-dried wood may have a higher fiber saturation point than the once-dried wood used to collect the data in table 8-4. Feist and Tarkow (1967), with a method which calls for soaking green wood in polyethelene glycol of molecular size too large to penetrate wood substance structure, found a higher fiber saturation point (40 percent) in never-dried green Sitka spruce (*Picea sitchensis* (Bong. Carr.) than in once-dried wood (31 percent). The Feist and Tarkow method applied to never-dried slash pine (*Pinus elliottii* Engelm.) indicated fiber saturation points substantially higher than those determined from the shrinkage observations of Nearn (1955), Higgins (1957), and Choong (1969ab). No data are available for southern hardwoods, but comparable differences are probable.

Feist and Tarkow (1967) and Kellogg and Wangaard (1969) both show negative correlations between specific gravity and fiber saturation point (fig. 8-6), especially at lower specific gravities. This relationship, perhaps limited to wood low in extractives, may explain some of the variation in fiber saturation point among species.

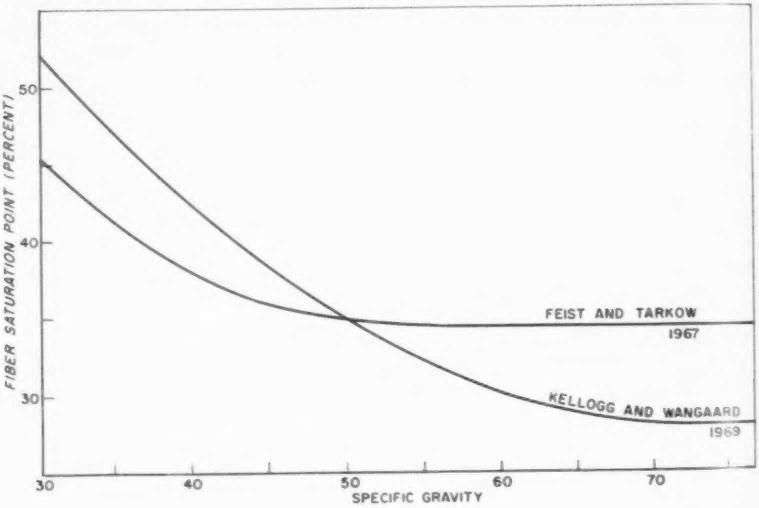

Figure 8-6.—Relation of fiber saturation point to wood specific gravity—basis of ovendry volume and weight. (Drawing after Kellog and Wangaard 1969.)

Wood with large extractive content may display an abnormally low fiber saturation point (Nearn 1955; Higgins 1957; Wangaard 1957; Spalt 1958; Wangaard and Granados 1967; Feist and Tarkow 1967; Choong 1969a). Apparently, extractives bulk the cell wall and thus preclude water from occupying the same space.

Rays in hardwoods have lower fiber saturation points than do surrounding tissues, possibly due to their different chemical composition. Morschauser (1954) found that broad rays of northern red oak had a fiber saturation point of only 12.0 percent moisture content; fiber tissues surrounding rays had a density only ⅔ that of the rays and a fiber saturation point of 27.8 percent.

The polymer exclusion method gives evidence that wood cellulose has much higher saturation points than solid wood. Figure 8-7 compares solid wood with cellophane (virtually pure cellulose) and with holocellulose.

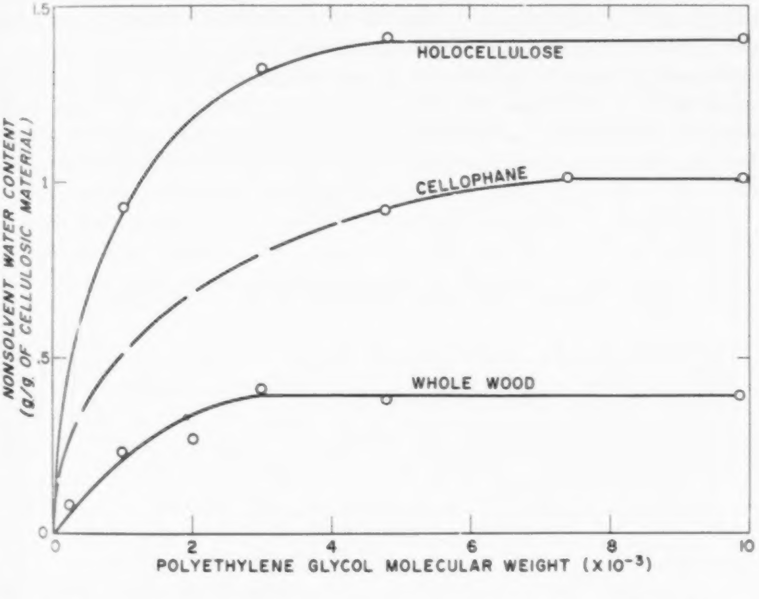

Figure 8-7.—Fiber saturation point of hard maple (40 percent of dry weight), cellulose in the form of cellophane (100 percent), and holocellulose (140 percent), as determined by soaking in polyethelene glycol of molecular size too large to penetrate substance structure. (Drawing after U.S. Department of Agriculture, Forest Service 1967, p. 8.)

Fiber saturation point of wood in liquids other than water is also of interest to wood technologists. Linear extrapolation of swelling versus liquid content to maximum swelling has been used to determine the fiber saturation point of once-dried yellow-poplar sapwood in non-aqueous liquids, as follows (Rosen and vanEtten 1974):

Solvent	Fiber saturation point	
	Average	Standard deviation
	Percent of dry weight	
Acetone	24.6	1.1
Dioxane	35.3	.9
Methanol	27.2	2.6
N-propanol	18.4	.6
Pyradine	58.6	.8

By the same method, Rosen and vanEtten's (1974) value for fiber saturation point of yellow-poplar wood in water was 31.5 percent with standard deviation of 0.3 percentage points. Fiber saturation points and swelling data of yellow-poplar and black oak in other non-aqueous liquids are given in table 8-12.

Carbonized wood has a substantially lower fiber saturation point in water than normal wood. Beall et al. (1974) found that yellow-poplar wood carbonized at 200°C had a fiber saturation point of about 24 percent, while that carbonized at 400°C had a fiber saturation point of only about 15 percent.

8-3 EQUILIBRIUM MOISTURE CONTENT

The weight of water vapor contained in a unit volume of space is called **absolute humidity;** it is usually expressed as the number of grains of moisture per cubic foot (7,000 grains = 1 pound avoirdupois). The capacity of air to hold water increases greatly at higher temperatures. Air containing the total number of grains of water that it can hold at its temperature is **saturated.**

Temperature	Absolute humidity (i.e., weight of moisture in saturated air at normal atmospheric pressure)
°F	*Grains per cubic foot*
20	1.2
60	5.8
100	20.0
140	56.9
180	139.3
200	208.1
212	261.1

Wood reaches an **equilibrium moisture content** (e.m.c.) if held in air at constant **relative humidity** and temperature. Relative humidity is the ratio of the water vapor actually in the air, to the amount present at saturation, dry air having 0-percent relative humidity, and saturated air 100 percent. It is usually determined from simultaneous readings on two thermometers, on one of which, the **wet bulb,** readings are depressed by evaporation from a wetted wick.

Analytical expressions that relate e.m.c. to relative humidity have potential use as a concise method to store and retrieve e.m.c.-relative humidity data (Simpson 1971) and in mathematical modeling. Among 10 sorption models tested on the basis of how well they related e.m.c. and relative humidity values as tabulated by the U.S. Department of Agriculture, Forest Service (1955, table 38 and reproduced here as table 8-6), Simpson (1973a) found that the Hailwood and Horrobin (1946) model is the most accurate for predicting moisture content as a function of relative humidity. The Pierce (1929) model was the most accurate of those tested for computing relative humidity as a function of moisture content.

SORPTION HYSTERESIS

For any condition of relative humidity and temperature, the equilibrium moisture content attained during **desorption** (drying from water-swollen condition) is greater than the e.m.c. attained during **adsorption** from the dry condition. Figure 8-8 illustrates an adsorption-desorption hysteresis loop for spruce (*Picea* spp.). Not all researchers have been able to observe that the hysteresis loop is closed at the upper end as illustrated (Wangaard and Granados 1967). Browning (1967, p. 317) states that a closed hysteresis loop is obtained only when desorption data are observed after adsorption data. It is believed that in the original green condition, the available polar hydroxyl groups in cell wall polymers are almost entirely satisfied by bound water. In dry wood which has lost its bound water, however, shrinkage brings the polar hydroxyl groups close enough together to satisfy each other; this results in diminished adsorption when rewetted.

Figure 8-9 illustrates a hysteresis loop for wood of southern hardwoods exposed to air of 25°C and up to 94 percent relative humidity. These data are specific to wood of 10 of the species in the collection described in table 3-1, i.e., green ash, white ash, American elm, hickory, red maple, southern red oak, white oak, sweetbay, sweetgum, and yellow-poplar. The mean sorption data for all 22 hardwoods (table 3-1) were not significantly different from data for the 10 selected woods (Okoh 1976, p. 25, 137, and 138). The curves through the data points of figure 8-9 are calculated isotherms based on the Hailwood and Horrobin (1946) model.

Okoh's (1976) data (see also Okoh and Skaar 1980) permitted computation of the ratio of adsorption moisture content to desorption moisture content at 25°C for the 10 species listed above throughout a range of relative humidities (fig. 8-10). The ratio was minimum (about 0.78) near 60-percent relative humidity and approached 0.85 as relative humidity approached 30 or 90 percent; the ratios for wood were consistently lower than those for bark of these species.

These ratio values fall close to values based on areas under sorption curves reported by Spalt (1958) for eight hardwoods (range 0.79 to 0.85), and by Wangaard and Granados (1967) for nine unextracted hardwoods, ranging from 0.74 to 0.82.

The equilibrium moisture content of extracted wood is higher than that of unextracted wood at relative humidities above 50 percent (Nearn 1955; Anderson 1961; Wangaard and Granados 1967; Rosen (1978).

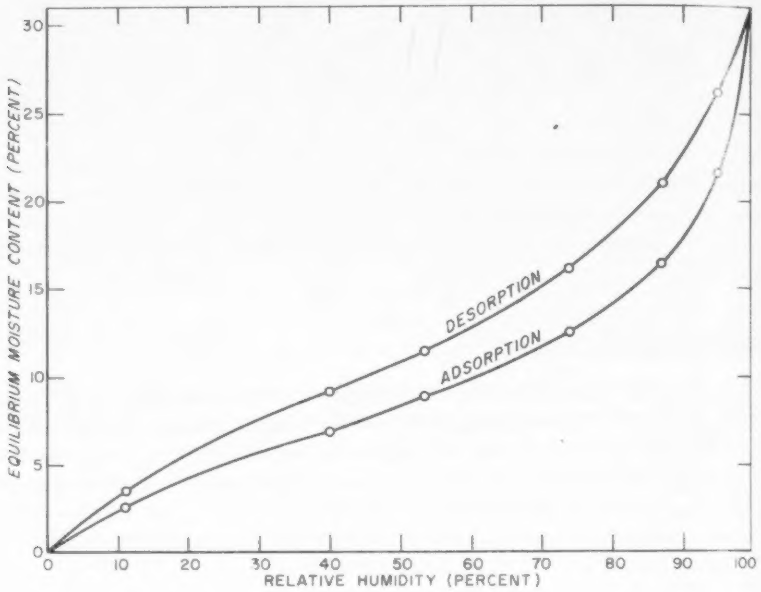

Figure 8-8.—Adsorption and desorption of water, expressed as a percentage of dry weight, by spruce at 25°C with changes in relative humidity. (Drawing after Alfred J. Stamm 1964, p. 146, WOOD AND CELLULOSE SCIENCE, Copyright 1964, the Ronald Press Company, New York.)

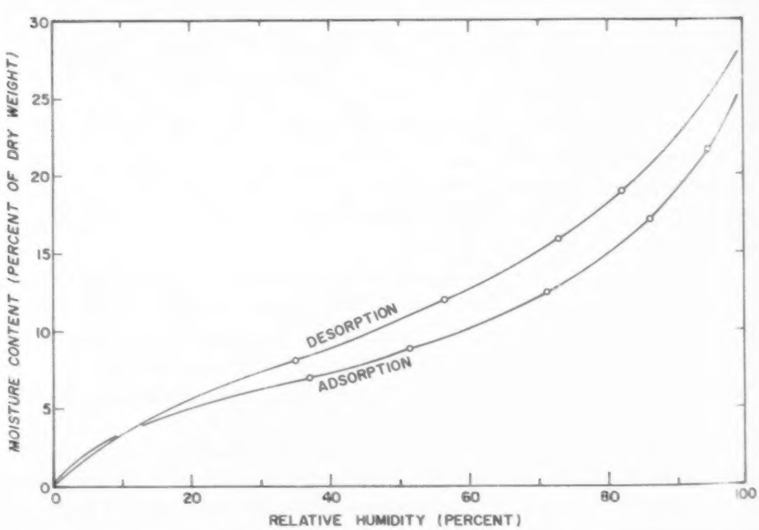

Figure 8-9.—Mean sorption isotherms for 10 southern hardwoods at 25°C. (Drawing after Okoh 1976, p. 27; Okoh and Skaar 1980.)

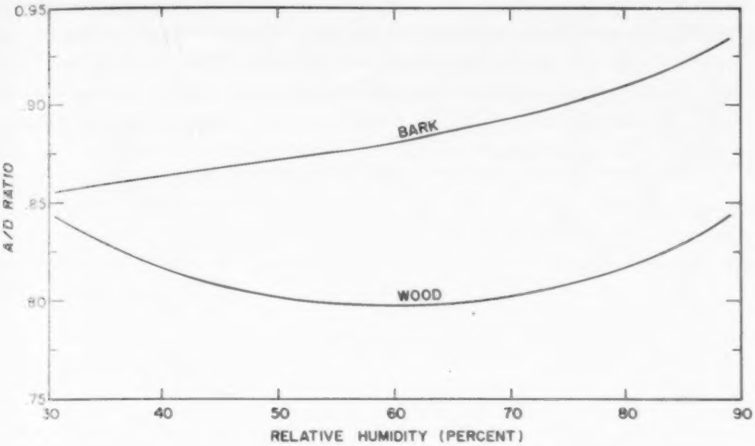

Figure 8-10.—Ratio of adsorption moisture content to desorption moisture content (A/D ratio) for wood and bark of 10 southern hardwoods related to relative humidity at 25°C. (Drawing after Okoh 1976, p. 39.)

EFFECT OF SPECIES AND TISSUE TYPE

At high relative humidities equilibrium moisture content varies slightly among southern hardwood species, but at low humidities differences appear to be minimal. Choong and Manwiller (1976) found that stemwood of 6-inch hardwoods from southern pine sites (table 3-1) did not differ significantly in e.m.c. among species at 25- or 50-percent relative humidity. At 25-percent relative humidity, e.m.c. averaged 5.1 percent, with coefficient of variation of 3.4 percent; at 50 percent, e.m.c. averaged 8.5 percent with coefficient of variation of 2.8 percent.

Differences among species were significant, however, at 71- and 85-percent relative humidities. At 71-percent humidity, for example, hickory contained significantly more moisture than any other species except sweetgum, and scarlet oak contained less than any other species except Shumard oak and green ash. At 85-percent, scarlet oak contained significantly less moisture than did white oak, winged elm, hickory and post oak, while Shumard oak contained less moisture than did hickory and post oak (table 8-5).

Okoh's (1976, p. 137) data for adsorption equilibrium moisture contents of these species at 71.2 percent relative humidity agree with the trends shown in table 8-5. At 94.2 percent relative humidity, Okoh found that during adsorption sweetgum had highest equilibrium moisture content (23.5 percent) and that red maple and black, scarlet, and northern red oaks had lowest equilibrium moisture contents (20.6 to 20.8 percent).

TABLE 8-5.—*Equilibrium moisture content of stemwood from 22 hardwood species at two conditions of relative humidity.*[1] *(values in parentheses are coefficients of variation)* (Data from Choong and Manwiller 1976)

Species	Equilibrium moisture content	
	71% RH[2]	85% RH[3]
	--Percent of dry weight -	
Ash, green	11.7 (1.8)	18.2 (2.3)
Ash, white	12.2 (2.2)	18.2 (2.5)
Elm, American	12.0 (2.2)	18.3 (2.6)
Elm, winged	12.1 (2.1)	18.6 (2.5)
Hackberry[4]	12.0 (3.3)	17.9 (3.1)
Hickory	12.6 (5.1)	18.8 (4.5)
Maple, red	12.0 (2.8)	17.6 (1.7)
Oak, black	11.9 (2.0)	17.9 (1.8)
Oak, blackjack	12.1 (2.2)	18.2 (2.8)
Oak, cherrybark	12.0 (2.5)	18.2 (2.8)
Oak, laurel	12.0 (2.2)	17.9 (1.8)
Oak, northern red	11.9 (3.0)	17.5 (3.0)
Oak, post	12.0 (1.7)	18.9 (2.1)
Oak, scarlet	11.4 (2.0)	17.0 (2.3)
Oak, Shumard	11.7 (2.6)	17.2 (2.6)
Oak, southern red	12.2 (2.4)	17.9 (1.5)
Oak, water	11.8 (2.5)	17.6 (2.1)
Oak, white	12.2 (2.0)	18.5 (1.9)
Sweetbay	11.8 (1.8)	17.8 (1.9)
Sweetgum	12.4 (2.1)	18.0 (2.8)
Tupelo, black	12.2 (1.9)	18.1 (3.2)
Yellow-poplar	12.0 (1.8)	17.6 (1.8)

[1] Dry-bulb temperature constant at 105°F.

[2] Species differences of 0.4 percentage points or more are statistically signficant at the 0.05 level of probability.

[3] Species differences of 1.4 percentage points or more are significant.

[4] Mostly sugarberry.

Permeability of cell walls differs with species, and these differences can influence apparent e.m.c. values of green wood during desorption. For example, Hart and Darwin (1971) and Hart et al. (1974) reported desorption e.m.c. values determined at 97-percent relative humidity at 40°C of 51 percent for white oak and 55 to 60 percent for hickory. The high e.m.c. values were attributed to free water trapped in completely saturated, imperforate cells.

In two southern hardwood species, stemwood e.m.c. may vary with radial distance from the pith. At 71-percent relative humidity, Choong and Manwiller (1976) found that the e.m.c. of **corewood,** i.e., wood close to the pith, but not necessarily heartwood, averaged significantly less than that of outer sapwood in yellow-poplar (11.9 and 12.1 percent), and in Shumard Oak (11.5 and 11.8 percent). In the other 20 species analyzed, differences in e.m.c. between corewood and outer sapwood were not significant.

Different tissues within stemwood of a species may ultimately attain the same e.m.c. during desorption, but their rate of moisture loss may vary. For example, radial moisture diffusion is 2 to 4 times more rapid in rays of white oak, northern red oak, and cherrybark than it is in the surrounding tissue. The ray tissue therefore dries faster than surrounding tissue, resulting in shrinkage stresses that probably contribute to formation of surface checks in ray ends on the tangential face of flat-sawn boards (Simpson 1973b).

Hardwood sorption characteristics may be altered by fungal attack. For example, *D. natalensis* infection increased by 20 to 25 percent the absortivity of air-dry southern hardwood, ¾-inch-square, end-coated sticks dipped in water for 15 minutes (Campbell 1959).

EFFECT OF STRESS

Simpson and Skaar (1968ab), in experiments with northern red oak have shown that application of a transverse compressive stress decreases wood e.m.c. The reduction in e.m.c. per unit of compressive stress increased with increasing moisture content and also appeared to increase with increasing stress levels. Stresses imposed ranged from 420 to 1,200 psi; wood under the maximum stress had an e.m.c. 0.44 percentage points below that of unstressed wood. Bello (1968) drew similar conclusions from his observation of five hardwoods.

Libby and Haygreen (1967) demonstrated on Douglas-fir (*Pseudotsuga menziessii* (Mirb.) Franco) that a transverse tensile stress slightly increased the e.m.c. of wood; when stressed at 60 percent of ultimate strength, wood had an e.m.c. less than 0.2 percentage point higher than when unstressed.

These empirical data and those of Simpson (1971) support the theory developed by Barkas (1949) and Barkas et al. (1953) to explain effects of stress on the moisture content of wood. Simpson (1971) summarized these effects, observed in northern red oak, as follows:

- The sorption isotherm of wood is stress dependent. The equilibrium moisture content of wood is increased by a tensile stress and decreased by a compressive stress.
- The moisture change per unit stress increases approximately exponentially with initial moisture content. The rate of increase is greater in tension than in compression, and the magnitude of the change is greater in tension than in compression.
- The moisture change per unit stress is greater for a tangential than for a radial stress.

Readers interested in computing pressures exerted by wood swelling under restraint will find the equations given by Skaar (1972, pp. 148, 150) useful.

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EFFECT OF TEMPERATURE ON EQUILIBRIUM MOISTURE CONTENT

At all relative humidities, the e.m.c. of wood is correlated with temperature; in the range from 25° to 100°C an increase in temperature reduces e.m.c. (fig. 8-11). Stamm and Loughborough (1935) reported this decrease as approximately 0.1 percent per °C increase between 25° and 100°C in Sitka spruce.

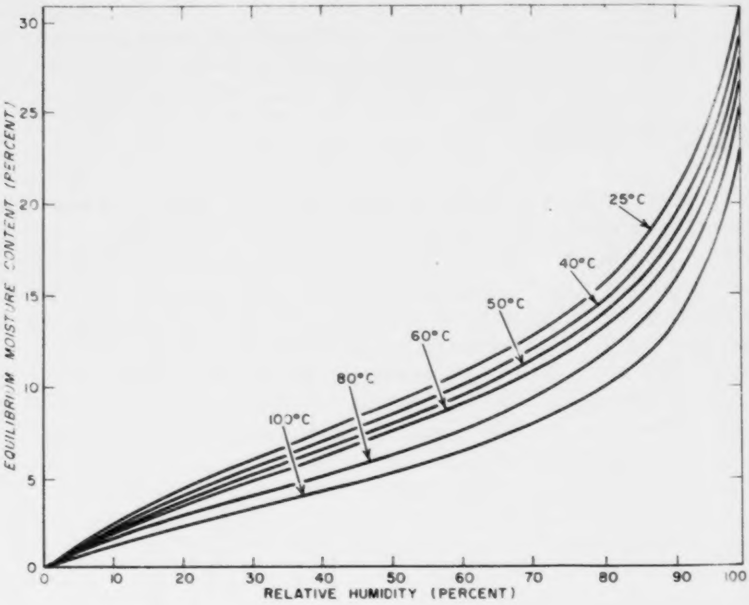

Figure 8-11.—Effect of temperature on the equilibrium moisture content (percent of dry weight) of a large Sitka spruce specimen during desorption. (Drawing after Alfred J. Stamm 1964, p. 152, WOOD AND CELLULOSE SCIENCE, Copyright 1964, The Ronald Press Company, New York.)

Dry wood heated to 200° or 300°C for a short time, or 100°C for a prolonged period, will experience a permanent decrease in both hygroscopicity and tendency to shrink and swell (Stamm et al. 1946; Stamm 1956). For example, Kollmann and Schneider (1963) observed the following effects:

Relative Humidity	Wood e.m.c. at 20°C following oven drying at temperatures of			
	70°C	130°C	150°C	180°C
Percent	*Percent of dry weight*			
30	7.0	6.0	5.5	4.5
50	9.5	8.5	8.0	6.0
70	13.0	12.0	10.5	7.5
90	18.0	17.0	15.0	10.5

Wood dried at 100°C had e.m.c. values less than ½ percentage point lower than those for wood dried at 70°C.

Steaming or boiling wood that has been through several desorption-adsorption cycles tends to restore its hygroscopic characteristics to those of never-dried green wood (Urquhart and Eckersall 1932; Seborg et al. 1938).

Kubinsky and Ifju (1974) found, however, that in cubes of never-dried green northern red oak measuring 24 mm on a side, steamed at atmospheric pressure for 1.5 to 96 hours, e.m.c. values diminished with increased steaming time (fig. 8-12).

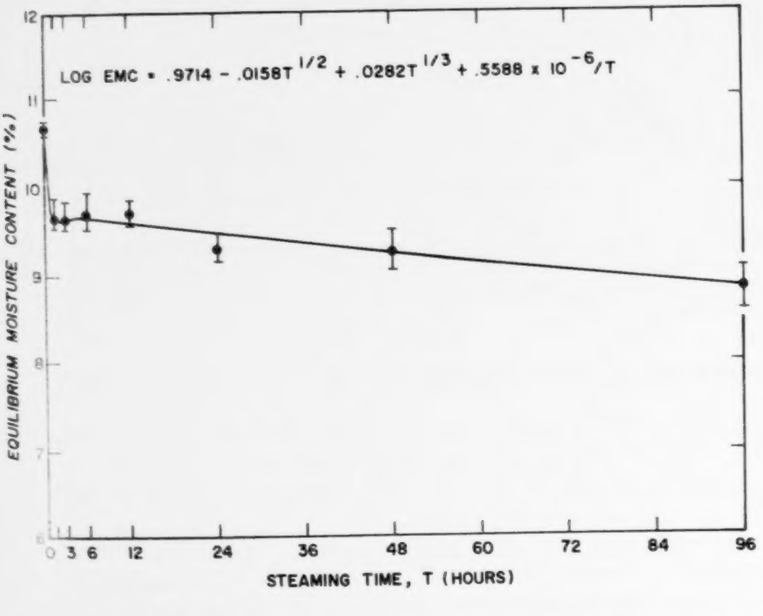

Figure 8-12.—Relationship between hours steamed at atmospheric pressure and equilibrium moisture content of northern red oak wood at 64-percent relative humidity and 25°C. Vertical lines indicate range of data and averages; the regression expression plotted accounts for 95 percent of observed variation with standard error of the estimate of 0.0061. (Drawing after Kubinsky and Ifju 1974.)

After wood has been exposed to carbonizing temperatures sorption isotherms of the resulting charcoal differ substantially from that of uncarbonized wood. Up to 400°C, e.m.c. of charcoal is inversely related to carbonization temperature (fig. 8-13). Beall et al. (1974) report identical sorption isotherms of yellow-poplar wood carbonized at 400°C and 600°C.

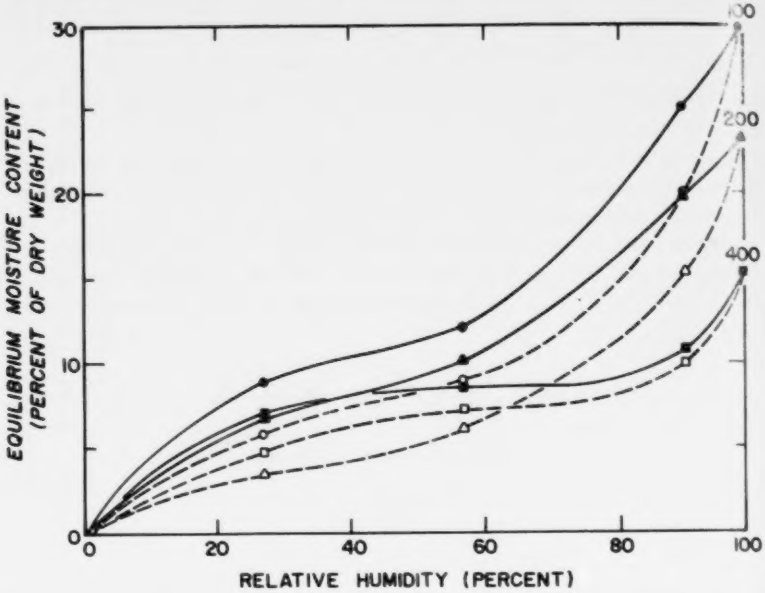

Figure 8-13.—Sorption isotherms at 28°C for yellow-poplar wood heated to 100°C, and matched specimens carbonized at 200° and 400°C. Solid lines and filled symbols represent desorption; dashed lines and open symbols denote adsorption. (Drawing after Beall et al. 1974.)

WORKING VALUES FOR EQUILIBRIUM MOISTURE CONTENT

It has been shown that the e.m.c. of wood varies with direction of sorption (figs. 8-8 and 8-9), species (table 8-5), location in tree (in some species), extractive content, temperature (fig. 8-11), temperature history of the specimen (fig. 8-12), and stress in the wood.

Such variation is sufficiently limited, however, that for many purposes it is convenient to assume that all wood in normal atmospheres attains the same e.m.c. under similar conditions of relative humidity and temperature. Table 8-6 arranged according to dry-bulb temperatures and wet-bulb depressions, provides useful approximations in the temperature range from 30° to 210°F. The e.m.c. for given conditions appears below the related relative humidity in the pair of lines to the right of the selected dry-bulb temperature.

Simpson (1982) found that the degree of control of relative humidity and temperature to maintain e.m.c. within desired limits during conditioning was highly dependent on relative humidity and temperature.

EQUILIBRIUM MOISTURE CONTENT AT LOW TEMPERATURES

The limited data available (none for southern hardwoods) indicate that e.m.c. patterns at temperatures below the freezing point of water differ somewhat from those shown in figure 8-11.

Hedlin (1967) observed sorption data for 12 different species at 10°, and 70°F. Isotherms obtained at 99-percent humidity and 10°F reach lower moisture contents than those obtained at 70°F, though the shapes are similar.

For wood of Sitka spruce and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), Schmidt (1967) found that at −20°C, sorption curves deviated considerably from the sigmoid shape shown in figure 8-8. The sorption isotherms were more or less linear from 10-percent relative humidity to vapor saturation, yielding a fiber saturation point of about 21-percent moisture content—a value much lower than one would expect from extrapolating the trend shown in figure 8-11.

Skaar (1972, p. 164) attributes low equilibrium moisture contents below the freezing point to more rapid decrease of vapor pressure in ice with decreasing temperature than in wood; therefore, cell walls yield excess moisture content which migrates to cell cavities where it condenses. Resulting shrinkage is much larger than normal thermal shrinkage of cell walls (Kubler 1962).

EQUILIBRIUM MOISTURE CONTENT ABOVE 212°F

Wood can be placed in a retort filled with steam, to the complete exclusion of air, and the steam in this vented retort heated at atmospheric pressure to above the boiling point of water. Under such circumstances, the e.m.c. of wood is negatively correlated with the temperature, e.g., the e.m.c. will be about 20 percent at 212°F and approximately 5 percent at 240°F (fig. 8-14).

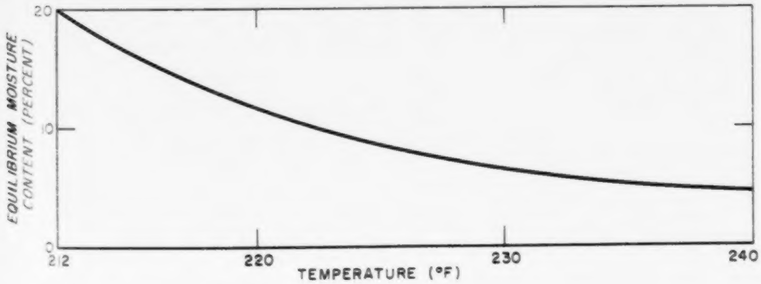

Figure 8-14.—Equilibrium moisture content of wood in superheated steam at atmospheric pressure. (Drawing after Kauman 1956.)

TABLE 8-6.—*Relationship of equilibrium moisture content to temperature and relative humidity* (Data from U.S. Department of Agriculture, Forest Service 1955, p. 312-313)

Temperature dry-bulb (°F.)	Wet-bulb depression (°F.)																																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	32	34	36	38	40	45	50
30	89	78	67	57	46	36	27	17	6	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	...	*15.9*	*12.9*	*10.8*	*9.0*	*7.4*	*5.7*	*3.9*	*1.6*	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
35	90	81	72	63	54	45	37	28	19	11	3	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	...	*16.8*	*13.9*	*11.9*	*10.3*	*8.8*	*7.4*	*6.0*	*4.5*	*2.9*	*0.8*	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
40	92	83	75	68	50	52	45	37	29	22	15	8	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	...	*17.6*	*14.8*	*12.9*	*11.2*	*9.9*	*8.6*	*7.4*	*6.2*	*5.0*	*3.5*	*1.9*	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
45	93	85	78	72	64	58	51	44	37	31	25	19	12	6	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	...	*18.3*	*15.6*	*13.7*	*12.0*	*10.7*	*9.5*	*8.5*	*7.5*	*6.5*	*5.3*	*4.2*	*2.9*	*1.5*	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
50	93	86	80	74	68	62	56	50	44	38	32	27	21	16	10	5	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	...	*19.0*	*16.3*	*14.4*	*12.7*	*11.5*	*10.3*	*9.4*	*8.5*	*7.6*	*6.7*	*5.7*	*4.8*	*3.9*	*2.8*	*1.5*	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
55	94	88	82	76	70	65	60	54	49	44	39	34	28	24	19	14	9	5	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	...	*19.5*	*16.9*	*15.1*	*13.4*	*12.2*	*11.0*	*10.1*	*9.3*	*8.4*	*7.6*	*6.8*	*6.0*	*5.3*	*4.5*	*3.6*	*2.5*	*1.3*	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
60	94	89	83	78	73	68	63	58	53	48	43	39	34	30	26	21	17	13	9	5	1	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	...	*19.9*	*17.4*	*15.6*	*13.9*	*12.7*	*11.6*	*10.7*	*9.9*	*9.1*	*8.3*	*7.6*	*6.9*	*6.3*	*5.6*	*4.9*	*4.1*	*3.2*	*2.3*	*1.3*	*0.2*	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
65	95	90	84	80	75	70	66	61	56	52	48	44	39	36	32	27	24	20	16	13	8	6	2	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	...	*20.3*	*17.8*	*16.1*	*14.4*	*13.3*	*12.1*	*11.2*	*10.4*	*9.7*	*8.9*	*8.3*	*7.7*	*7.1*	*6.5*	*5.8*	*5.2*	*4.5*	*3.8*	*3.0*	*2.3*	*1.4*	*0.4*	...	...	...	...	...	...	...	...	...	...	...	...	...	...
70	95	90	86	81	77	72	68	64	59	55	51	48	44	40	36	33	29	25	22	19	15	12	9	6	3	...	...	...	...	...	...	...	...	...	...	...	...
	...	*20.6*	*18.2*	*16.5*	*14.9*	*13.7*	*12.5*	*11.6*	*10.9*	*10.1*	*9.4*	*8.8*	*8.3*	*7.7*	*7.2*	*6.6*	*6.0*	*5.5*	*4.9*	*4.3*	*3.7*	*2.9*	*2.3*	*1.5*	*0.7*	...	...	...	...	...	...	...	...	...	...	...	...
75	95	91	86	82	78	74	70	66	62	58	54	51	47	44	41	37	34	31	28	24	21	18	15	12	10	7	4	1	...	...	...	...	...	...	...	...	...
	...	*20.9*	*18.5*	*16.8*	*15.2*	*14.0*	*12.9*	*12.0*	*11.2*	*10.5*	*9.8*	*9.3*	*8.7*	*8.2*	*7.7*	*7.2*	*6.7*	*6.2*	*5.6*	*5.1*	*4.7*	*4.1*	*3.5*	*2.9*	*2.3*	*1.7*	*0.9*	*0.2*	...	...	...	...	...	...	...	...	...
80	96	91	87	83	79	75	72	68	64	61	57	54	50	47	44	41	38	35	32	29	26	23	20	18	15	12	10	7	5	3	...	...	...	...	...	...	...
	...	*21.0*	*18.7*	*17.0*	*15.5*	*14.3*	*13.2*	*12.3*	*11.5*	*10.9*	*10.1*	*9.7*	*9.1*	*8.6*	*8.1*	*7.7*	*7.2*	*6.8*	*6.3*	*5.8*	*5.4*	*5.0*	*4.5*	*4.0*	*3.5*	*3.0*	*2.4*	*1.8*	*1.1*	*0.3*	...	...	...	...	...	...	...
85	96	92	88	84	80	76	73	70	66	63	59	56	53	50	47	44	41	38	36	33	30	28	25	23	20	18	15	13	11	9	4	...	...	...	...	...	...
	...	*21.2*	*18.8*	*17.2*	*15.7*	*14.5*	*13.5*	*12.5*	*11.8*	*11.2*	*10.5*	*10.0*	*9.5*	*9.0*	*8.5*	*8.1*	*7.6*	*7.2*	*6.7*	*6.3*	*6.0*	*5.6*	*5.2*	*4.8*	*4.3*	*3.9*	*3.4*	*3.0*	*2.4*	*1.7*	*0.9*	...	...	...	...	...	...
90	96	92	89	85	81	78	74	71	68	65	61	58	55	52	49	47	44	41	39	36	34	31	29	26	24	22	19	17	15	13	9	5	1	...	...	...	...
	...	*21.3*	*18.9*	*17.3*	*15.9*	*14.7*	*13.7*	*12.8*	*12.0*	*11.4*	*10.7*	*10.2*	*9.7*	*9.3*	*8.8*	*8.4*	*8.0*	*7.6*	*7.2*	*6.8*	*6.5*	*6.1*	*5.7*	*5.3*	*4.9*	*4.6*	*4.2*	*3.8*	*3.3*	*2.8*	*2.1*	*1.3*	*0.4*	...	...	...	...
95	96	92	89	85	82	79	75	72	69	66	63	60	57	55	52	49	46	44	42	39	37	34	32	30	28	26	23	22	20	17	14	10	6	2	...	...	...
	...	*21.3*	*19.0*	*17.4*	*16.1*	*14.9*	*13.9*	*12.9*	*12.2*	*11.6*	*11.0*	*10.5*	*10.0*	*9.5*	*9.1*	*8.7*	*8.2*	*7.9*	*7.5*	*7.1*	*6.8*	*6.4*	*6.1*	*5.7*	*5.3*	*5.1*	*4.8*	*4.4*	*4.0*	*3.6*	*3.0*	*2.3*	*1.5*	*0.6*	...	...	...
100	96	93	89	86	83	80	77	73	70	68	65	62	59	56	54	51	49	46	44	41	39	37	35	33	30	28	26	24	22	21	17	13	10	7	4	...	...
	...	*21.3*	*19.0*	*17.5*	*16.1*	*15.0*	*13.9*	*13.1*	*12.4*	*11.8*	*11.2*	*10.6*	*10.1*	*9.6*	*9.2*	*8.9*	*8.5*	*8.1*	*7.8*	*7.4*	*7.0*	*6.7*	*6.4*	*6.1*	*5.7*	*5.4*	*5.2*	*4.9*	*4.6*	*4.2*	*3.6*	*3.1*	*2.4*	*1.6*	*0.7*	...	...

TABLE 8-6.—*Relationship of equilibrium moisture content to temperature and relative humidity* (Data from U.S. Department of Agriculture, Forest Service 1955, p. 312-313)—Continued

Temperature, dry-bulb (°F.)	Wet-bulb depression (°F.)																																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	32	34	36	38	40	45	50
105	96	93	90	87	83	80	77	74	71	69	66	63	60	58	55	53	50	48	46	44	42	40	37	35	34	31	29	28	26	24	20	17	14	11	8	...	...
	...	*21.4*	*19.0*	*17.5*	*16.2*	*15.1*	*14.0*	*13.2*	*12.6*	*11.9*	*11.3*	*10.8*	*10.3*	*9.8*	*9.4*	*9.0*	*8.7*	*8.3*	*7.9*	*7.6*	*7.3*	*6.9*	*6.7*	*6.4*	*6.1*	*5.7*	*5.4*	*5.2*	*4.8*	*4.6*	*4.2*	*3.6*	*3.1*	*2.4*	*1.8*	...	...
110	97	93	90	87	84	81	78	75	73	70	67	65	62	60	57	55	52	50	48	46	44	42	40	38	36	34	32	30	28	26	23	20	17	14	11	4	...
	...	*21.4*	*19.0*	*17.5*	*16.2*	*15.1*	*14.1*	*13.3*	*12.6*	*12.0*	*11.4*	*10.8*	*10.4*	*9.9*	*9.5*	*9.2*	*8.8*	*8.4*	*8.1*	*7.7*	*7.5*	*7.2*	*6.8*	*6.6*	*6.3*	*6.0*	*5.7*	*5.4*	*5.2*	*4.8*	*4.5*	*4.0*	*3.5*	*3.0*	*2.5*	*1.1*	...
115	97	93	90	88	85	82	79	76	74	71	68	66	63	61	58	56	54	52	50	48	45	43	41	40	38	36	34	32	31	29	26	23	20	17	14	8	2
	...	*21.4*	*19.0*	*17.5*	*16.2*	*15.1*	*14.1*	*13.4*	*12.7*	*12.1*	*11.5*	*10.9*	*10.4*	*10.0*	*9.6*	*9.3*	*8.9*	*8.6*	*8.2*	*7.8*	*7.6*	*7.3*	*7.0*	*6.7*	*6.5*	*6.2*	*5.9*	*5.6*	*5.4*	*5.2*	*4.7*	*4.3*	*3.9*	*3.4*	*2.9*	*1.7*	*0.4*
120	97	94	91	88	85	82	80	77	74	72	69	67	65	62	60	58	55	53	51	49	47	45	43	41	40	38	36	34	33	31	28	25	22	19	17	10	5
	...	*21.3*	*19.0*	*17.4*	*16.2*	*15.1*	*14.1*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.5*	*10.0*	*9.7*	*9.4*	*9.0*	*8.7*	*8.3*	*7.9*	*7.7*	*7.4*	*7.2*	*6.8*	*6.6*	*6.3*	*6.1*	*5.8*	*5.6*	*5.4*	*5.0*	*4.6*	*4.2*	*3.7*	*3.3*	*2.3*	*1.1*
125	97	94	91	88	86	83	80	77	75	73	70	68	65	63	61	59	57	55	53	51	48	47	45	43	41	39	38	36	35	33	30	27	24	22	19	13	8
	...	*21.2*	*18.9*	*17.3*	*16.1*	*15.0*	*14.0*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.5*	*10.0*	*9.7*	*9.4*	*9.0*	*8.7*	*8.3*	*8.0*	*7.7*	*7.5*	*7.2*	*7.0*	*6.7*	*6.5*	*6.2*	*6.0*	*5.8*	*5.5*	*5.2*	*4.8*	*4.4*	*4.0*	*3.6*	*2.7*	*1.6*
130	97	94	91	89	86	83	81	78	76	73	71	69	67	64	62	60	58	56	54	52	50	48	47	45	43	41	40	38	37	35	32	29	26	24	21	15	10
	...	*21.0*	*18.8*	*17.2*	*16.0*	*14.9*	*14.0*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.5*	*10.0*	*9.7*	*9.4*	*9.0*	*8.7*	*8.3*	*8.0*	*7.8*	*7.6*	*7.3*	*7.0*	*6.8*	*6.6*	*6.4*	*6.1*	*5.9*	*5.6*	*5.3*	*4.9*	*4.6*	*4.2*	*3.8*	*3.0*	*2.0*
140	97	95	92	89	87	84	82	79	77	75	73	70	68	66	64	62	60	58	56	54	53	51	49	47	46	44	43	41	40	38	35	32	30	27	25	19	14
	...	*20.7*	*18.6*	*16.9*	*15.8*	*14.8*	*13.8*	*13.2*	*12.5*	*11.9*	*11.4*	*10.9*	*10.4*	*10.0*	*9.6*	*9.4*	*9.0*	*8.7*	*8.4*	*8.0*	*7.8*	*7.6*	*7.3*	*7.1*	*6.9*	*6.6*	*6.4*	*6.2*	*6.0*	*5.8*	*5.4*	*5.1*	*4.8*	*4.4*	*4.1*	*3.4*	*2.6*
150	98	95	92	90	87	85	82	80	78	76	74	72	70	68	66	64	62	60	58	57	55	53	51	49	48	46	45	43	42	41	38	36	33	30	28	23	18
	...	*20.2*	*18.4*	*16.6*	*15.4*	*14.5*	*13.7*	*13.0*	*12.4*	*11.8*	*11.2*	*10.8*	*10.3*	*9.9*	*9.5*	*9.2*	*8.9*	*8.6*	*8.3*	*8.0*	*7.8*	*7.5*	*7.3*	*7.1*	*6.9*	*6.7*	*6.4*	*6.2*	*6.0*	*5.8*	*5.4*	*5.2*	*4.9*	*4.5*	*4.2*	*3.6*	*2.9*
160	98	95	93	90	88	86	83	81	79	77	75	73	71	69	67	65	64	62	60	58	57	55	53	52	50	49	47	46	44	43	41	38	35	33	31	25	21
	...	*19.8*	*18.1*	*16.2*	*15.2*	*14.2*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.6*	*10.1*	*9.7*	*9.4*	*9.1*	*8.8*	*8.5*	*8.2*	*7.9*	*7.7*	*7.4*	*7.2*	*7.0*	*6.8*	*6.7*	*6.4*	*6.2*	*6.0*	*5.8*	*5.5*	*5.2*	*4.9*	*4.6*	*4.3*	*3.7*	*3.2*
170	98	95	93	91	89	86	84	82	80	78	76	74	72	70	69	67	65	63	62	60	59	57	55	53	52	51	49	48	47	45	43	40	38	35	33	28	24
	...	*19.4*	*17.7*	*15.8*	*14.8*	*13.9*	*13.2*	*12.4*	*11.8*	*11.3*	*10.8*	*10.4*	*9.9*	*9.6*	*9.2*	*9.0*	*8.6*	*8.4*	*8.0*	*7.8*	*7.6*	*7.3*	*7.2*	*6.9*	*6.7*	*6.6*	*6.4*	*6.2*	*6.0*	*5.7*	*5.5*	*5.2*	*4.9*	*4.6*	*4.4*	*3.7*	*3.2*
180	98	96	94	91	89	87	85	83	81	79	77	75	73	72	70	68	67	65	63	62	60	58	57	55	54	52	51	50	48	47	45	42	40	38	35	30	26
	...	*18.9*	*17.3*	*15.5*	*14.5*	*13.7*	*12.9*	*12.2*	*11.6*	*11.1*	*10.6*	*10.1*	*9.7*	*9.4*	*9.0*	*8.8*	*8.4*	*8.1*	*7.8*	*7.6*	*7.4*	*7.2*	*7.0*	*6.8*	*6.5*	*6.4*	*6.2*	*6.0*	*5.8*	*5.7*	*5.4*	*5.2*	*4.8*	*4.6*	*4.4*	*3.8*	*3.3*
190	98	96	94	92	90	88	85	84	82	80	78	76	75	73	71	69	68	66	65	63	62	60	58	57	56	54	53	51	50	49	46	44	42	39	37	32	28
	...	*18.5*	*16.9*	*15.2*	*14.2*	*13.4*	*12.7*	*12.0*	*11.4*	*10.9*	*10.5*	*10.0*	*9.6*	*9.2*	*8.9*	*8.6*	*8.2*	*7.9*	*7.7*	*7.4*	*7.2*	*7.0*	*6.8*	*6.6*	*6.4*	*6.2*	*6.0*	*5.9*	*5.7*	*5.5*	*5.3*	*5.0*	*4.8*	*4.5*	*4.4*	*3.8*	*3.3*
200	98	96	94	92	90	88	86	84	82	80	79	77	75	74	72	70	69	67	66	64	63	61	60	58	57	55	54	53	52	51	48	46	43	41	39	34	30
	...	*18.1*	*16.4*	*14.9*	*14.0*	*13.2*	*12.4*	*11.8*	*11.2*	*10.8*	*10.3*	*9.8*	*9.4*	*9.1*	*8.8*	*8.4*	*8.1*	*7.7*	*7.5*	*7.2*	*7.0*	*6.9*	*6.6*	*6.4*	*6.2*	*6.0*	*5.9*	*5.7*	*5.6*	*5.4*	*5.2*	*4.9*	*4.7*	*4.5*	*4.3*	*3.8*	*3.3*
210	98	96	94	92	90	88	86	85	83	81	79	78	76	75	73	71	70	68	67	65	64	63	61	60	59	57	56	54	53	52	50	47	45	43	41	36	32
	...	*17.7*	*16.0*	*14.6*	*13.8*	*13.0*	*12.2*	*11.7*	*11.1*	*10.6*	*10.0*	*9.7*	*9.2*	*9.0*	*8.7*	*8.3*	*8.0*	*7.6*	*7.4*	*7.1*	*6.9*	*6.8*	*6.5*	*6.3*	*6.1*	*5.9*	*5.8*	*5.5*	*5.4*	*5.3*	*5.1*	*4.8*	*4.6*	*4.4*	*4.2*	*3.7*	*3.2*

[1] Relative humidity values in roman type.

[2] Equilibrium moisture content values in italic type.

If air is admitted to the retort so that the steam is no longer saturated, then the e.m.c. of wood is determined by the dry-bulb temperature and the relative humidity. At temperatures above the boiling point of water—as at lower temperatures—the relative vapor pressure is:

$$\left(\frac{\text{partial pressure of water vapor in the atmosphere at dry-bulb temperature, t.}}{\text{pressure of saturated water vapor at the same dry-bulb temperature, t}}\right);$$

relative humidity is this value multiplied by 100. The partial pressure of water vapor in an air-vapor mixture at any dry-bulb temperature (whether above or below 212°F) is the vapor pressure at the prevailing wet-bulb temperature. For example, at a dry-bulb temperature of 240°F and a wet-bulb temperature of 160°F, the partial water vapor pressure is 4.739 psi absolute, and the pressure of saturated water vapor is 24.97 psi. Therefore, the relative vapor pressure is 0.19, and the relative humidity is 19 percent.

TABLE 8-7.—*Relationship of equilibrium moisture content to temperature and relative humidity of air-steam mixtures at atmospheric pressure and above 212°F* (Data from Ladell 1957)[1]

Wet-bulb Temperature (°F.)	Dry-bulb Temperature—(°F.)										
	260	255	250	245	240	235	230	225	220	215	212
212.........	42	45	49	53	59	65	70	77	85	94	100
	3·1	*3·4*	*3·8*	*4·2*	*5·0*	*5·8*	*6·9*	*8·7*	*11·3*	*15·5*	*19·5*
210.........	40	43	47	51	56	61	67	74	82	90	98
	2·9	*3·3*	*3·6*	*4·0*	*4·7*	*5·4*	*6·3*	*8·0*	*10·4*	*14·0*	*17·0*
205.........	36	39	43	47	51	55	61	67	74	82	88
	2·7	*3·0*	*3·4*	*3·8*	*4·2*	*4·7*	*5·5*	*6·6*	*8·3*	*10·7*	*13·0*
200.........	32	36	39	42	46	51	55	62	67	74	79
	2·4	*2·8*	*3·1*	*3·4*	*3·8*	*4·3*	*4·9*	*5·8*	*6·9*	*8·7*	*10·0*
195.........	30	32	35	38	42	46	51	56	61	66	69
	2·2	*2·5*	*2·8*	*3·1*	*3·5*	*3·9*	*4·5*	*5·1*	*5·9*	*7·0*	*7·6*
190.........	26	28	30	34	37	40	44	48	52	58	61
	2·0	*2·2*	*2·4*	*2·8*	*3·1*	*3·4*	*3·8*	*4·3*	*5·0*	*5·7*	*6·2*
185.........	23	25	28	30	32	35	39	42	47	52	55
	1·8	*2·0*	*2·2*	*2·5*	*2·7*	*3·0*	*3·4*	*3·7*	*4·3*	*5·0*	*5·4*
180.........	20	22	24	27	29	31	35	38	42	47	50
	1·6	*1·8*	*2·0*	*2·3*	*2·5*	*2·7*	*3·1*	*3·4*	*3·9*	*4·5*	*4·9*
175.........	19	20	22	24	26	29	32	35	38	43	45
	1·5	*1·6*	*1·8*	*2·0*	*2·2*	*2·5*	*2·8*	*3·2*	*3·5*	*4·0*	*4·4*
170.........	17	18	20	22	24	26	28	31	34	38	40
	1·3	*1·5*	*1·7*	*1·9*	*2·1*	*2·3*	*2·5*	*2·8*	*3·2*	*3·5*	*3·8*
165.........	15	16	17	19	21	23	25	28	31	34	36
	1·2	*1·3*	*1·4*	*1·6*	*1·9*	*2·1*	*2·3*	*2·6*	*2·9*	*3·3*	*3·5*
160.........	13	14	16	17	19	21	23	25	27	30	32
	1·0	*1·2*	*1·3*	*1·5*	*1·7*	*1·9*	*2·1*	*2·3*	*2·6*	*2·9*	*3·1*

[1] In body of table, the upper figure is percent relative humidity, and the lower is percent e.m.c.

In 1926 the U.S. Forest Products Laboratory prepared curves which, when mathematically extrapolated, provided e.m.c. data to 248°F (U.S. Department of Agriculture, Forest Service 1957). Kauman (1956, p. 330) has provided graphs showing the e.m.c. for wood in steam-air mixtures above the boiling point of water; from these curves (based on data of A. J. Stamm, W. K. Loughborough, and R. Keylwerth) the Forest Products Laboratories of Canada have published the e.m.c. data shown in table 8-7.

Readers needing additional information should find useful the following publications:

Reference	Subject
Rosen (1980)	Psychrometric relationships and equilibrium moisture content of wood at temperatures above 212°F
Simpson and Rosen (1981)	Equilibrium moisture content of wood at high temperatures
Kent et al. (1981)	Determination of equilibrium moisture content of yellow-poplar sapwood above 100°C

EQUILIBRIUM MOISTURE CONTENT OF RECONSTITUTED WOOD

Particleboards, hardboards, and high-pressure decorative laminates are commonly used in the relatively narrow temperature range from 60° to 90°F. Their moisture contents change, however, with variations in relative humidity. As with solid wood, e.m.c. values observed during desorption are higher than during adsorption. Because of resins, waxes, and other additives incorporated in these products, and because of the high temperatures they experience during pressing, their e.m.c. values are characteristically lower than those of solid wood. Heebink (1966) has published some average e.m.c. values that are useful even though it is recognized that the e.m.c. of these products varies considerably with brand, resin content, pressing cycle, and raw material. Comparative data on solid wood are taken from table 8–6.

	Equilibrium moisture content			
Percent relative humidity at 70°F	Solid wood	Particleboard	Tempered hardboard	Decorative laminate
	Percent of dry weight			
30	6.0	6.6	4.0	3.0
42	8.0	7.5	4.6	3.3
65	12.0	9.3	6.9	5.1
80	16.1	11.6	9.5	6.6
90	20.6	16.6	10.8	9.1

Tempered hardboard, i.e., hardboard treated with hydrophobic oils during manufacture, has lower e.m.c. than untreated hardboards (fig. 8-15). Dense fiberboards (hardboards) have lower e.m.c. than medium-density fiberboards, hardwood particle boards, or fiber insulation boards; plywood e.m.c. closely approaches that of solid wood (table 8-8).

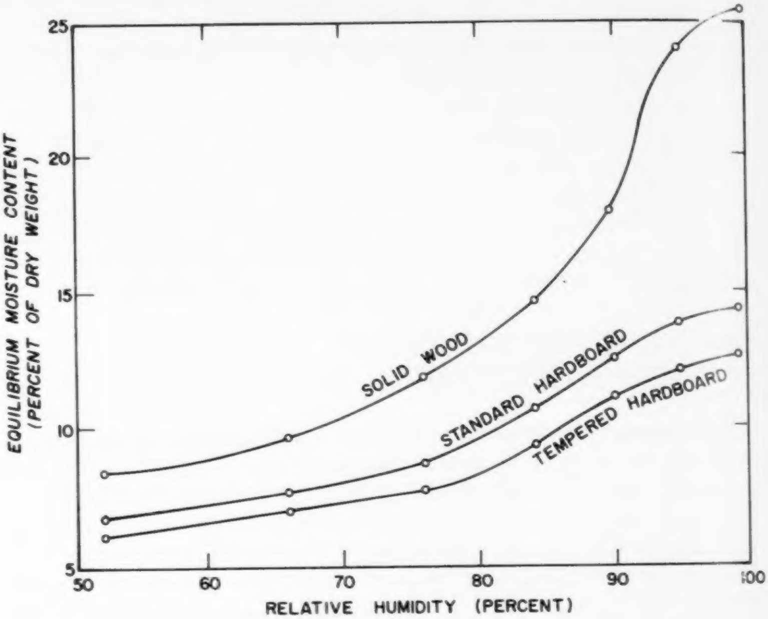

Figure 8-15.—Sorption isotherm of Scotch pine (*Pinus sylvestris* L.) sapwood compared with those of standard and tempered 3.2 mm hardboard at 22°C. (Drawing after Princes Risborough Laboratory 1975.)

Sorption hysteresis loops published in the literature show that tempered hardboard has lower e.m.c. values throughout a range of relative humidities than does exterior flakeboard of southern hardwood species; medium-density fiberboard of sweetgum has a sorption isotherm similar to that of flakeboard (fig. 8-16, 8-17, and 8-18).

TABLE 8-8.—*Water sorption of a variety of reconstituted panel products at 50-, and 90-percent relative humidity and after a 24-hour water soak* (Data from Chow 1976)

Product	Equilibrium moisture content at 70°F and 50% relative humidity	Equilibrium moisture content at 70°F and 90% relative humidity	Water absorption after 24 hours of soaking in water
	Percent of dry weight		
Tempered ¼-inch hardboard	3.5	7.0	9.0
Seven hardboards ¼ to ⅜-inch thick	4.9	9.4	12.0
¾-inch medium-density fiberboard (U-F)	5.3	11.0	15.0
¾-inch mixed hardwood particleboard (U–F)	6.1	15.3	34.1
½-inch fiber insulation board sheathing.	5.6	18.0	20.0
¾-inch, 13-ply birch (*Betula* spp.) plywood (U–F).	6.0	20.0	55.5
½-inch waste-paper board . .	7.0	22.8	27.5
Solid wood[2]	9.2	20.6	—

[1] U–F means urea-formaldehyde binder or adhesive.
[2] From table 8-6.

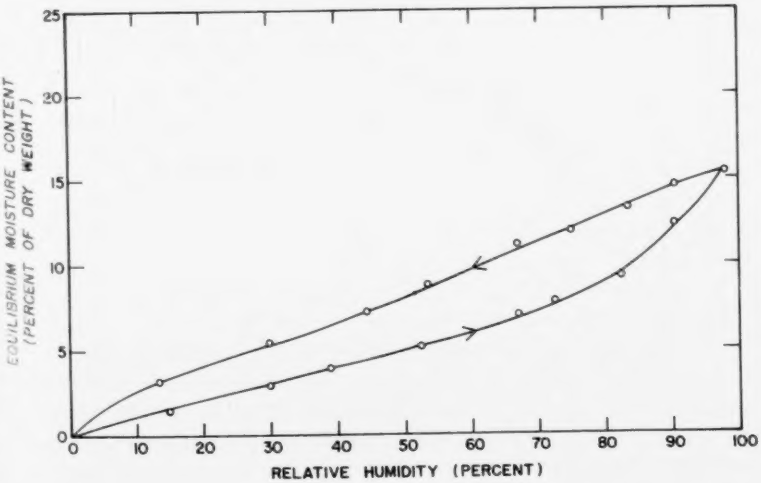

Figure 8-16.—Adsorption and desorption isotherms at 20°C for heat-treated hardboard. (Drawing after Bristow and Back 1969.)

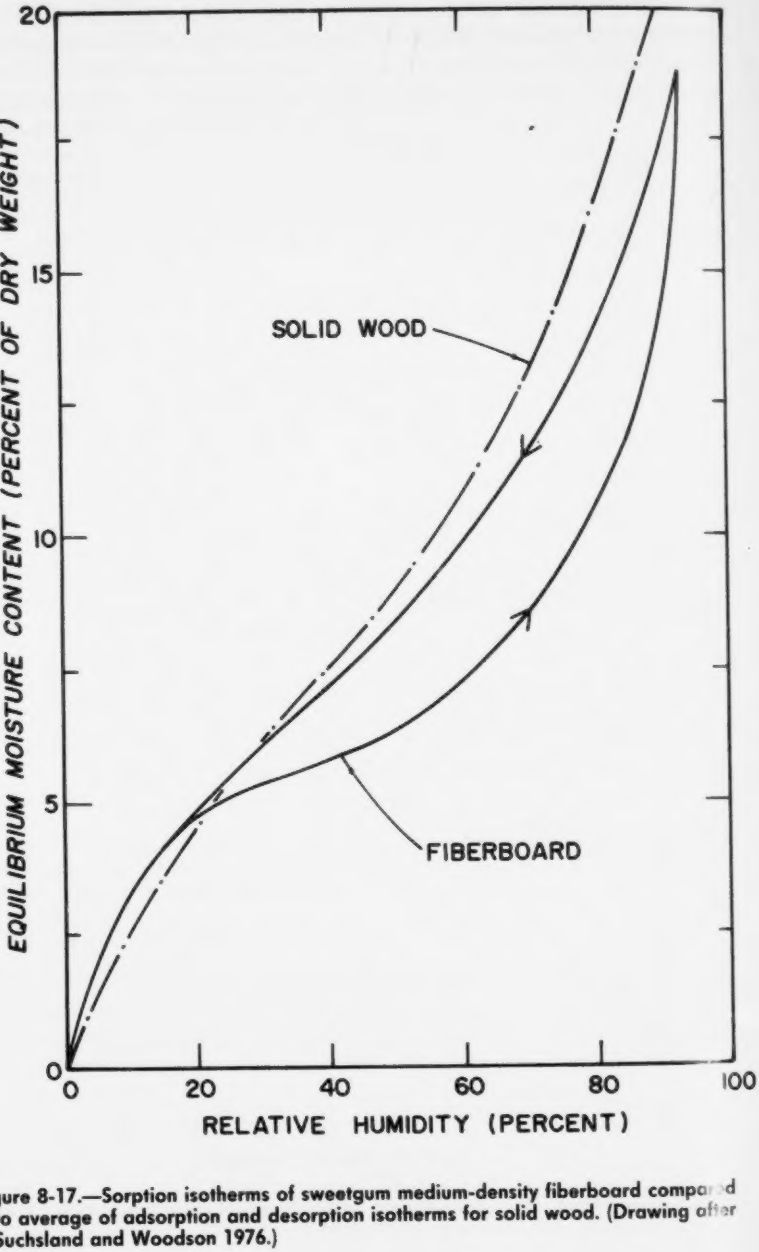

Figure 8-17.—Sorption isotherms of sweetgum medium-density fiberboard compared to average of adsorption and desorption isotherms for solid wood. (Drawing after Suchsland and Woodson 1976.)

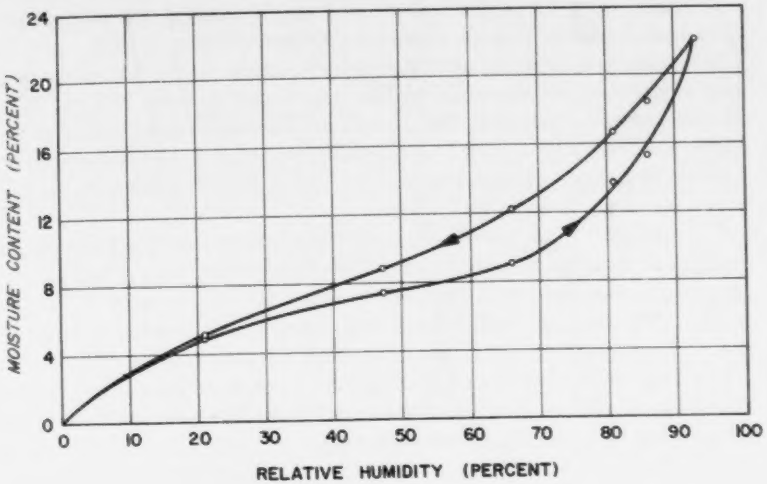

Figure 8-18.—Sorption isotherm of ½-inch structural flakeboard comprised of equal-weight portions of hickory species, white oak, southern red oak, sweetgum, and southern pine species. Density of the board when dry was about 46 pounds per cubic foot and it contained 6 percent phenol-formaldehyde resin and 1 percent wax. (Drawing after E. W. Price. 1979. Final Report FS-SO-3201-3.14, South. For. Exp. Stn., U.S. Dep. Agric. For. Serv., Pineville, La.)

An evaluation of six particleboards with urea-formaldehyde binder and six ¼-inch tempered hardboards manufactured in North America yielded the following e.m.c. values at 80°F (McNatt 1974ab):

	Equilibrium moisture content		
Relative humidity	Hardboard	U–F particleboard	Solid wood
Percent	*Percent of dry weight*		
30	4.0	6.0	6.1
50	5.1	8.3	9.1
65	6.9	9.5	11.7
80	9.5	12.0	15.7
90	10.9	16.0	20.2

MOISTURE CONTENT OF WOOD IN USE

To reduce adverse effects of shrinking and swelling in use, wood should be put in place at a moisture content in equilibrium with the atmosphere in which it serves. For example, posts to be set in wet soil can be pressure treated and installed at 30-percent moisture content or higher.

On the other hand solid structural lumber, or rafters laminated from hardwood veneers, for use in unheated structures should be installed at a moisture content corresponding to the e.m.c. for average outside conditions, e.g., approximately 9 percent for the dry southwestern states and 12 percent for the rest of the United States. Tank stock, truck or car decking, and ship lumber should serve well if manufactured at about 12 percent moisture content.

Structural wood for southern homes without air conditioning will probably serve best if dried to 10-percent moisture content (Hopkins 1960).

Increasingly in the major market areas for southern woods, houses and commercial structures are air conditioned the year around to about 75°F and 25- to 50-percent relative humidity. Table 8-6 shows that wood placed in such atmospheres will reach an e.m.c. of 5 to 9 percent. Hardwood paneling, flooring, and furniture placed in such heated and cooled spaces should therefore be installed within this range of moisture contents.

For example, Taras (1967) found that unfinished wood placed in an air-conditioned bowling alley in Bristol, Tennessee varied from a high of 7.6-percent moisture content in early fall to a low of 4.5 percent in the spring. Hardwood flooring and pins in this bowling alley would therefore serve best if manufactured and installed at about 6-percent moisture content.

Finished furniture parts manufactured in one location for assembly in another, should be equilibrated, machined, and inspected for size tolerance under atmospheric conditions matching those of the assembly location; conditions at assembly should in turn match those of the intended point of furniture use.

Lumber used in large laminated members should be slightly drier than the moisture content expected in service; thus, moisture absorbed from the glue will not raise the moisture content of the product above the service value. Moisture content should not vary more than 5 percent among laminates in a single member (U.S. Department of Agriculture, Forest Service 1974, p. 14-4). Year-round national average moisture content for laminated timbers in protected exterior exposure is 9 percent; for interior exposure, 8 percent (Hann et al. 1970).

Hardwood parts made for industrial purposes, such as handles, shuttles and bobbins, and shoe-last blocks should be manufactured at a moisture content of 5 to 7 percent.

Products reconstituted from hardwood particles and fibers will be manufactured in increasing quantities. These particleboards, flakeboards, fiberboards, and decorative laminates have lower e.m.c. values than solid wood. For such products it is more meaningful to specify that they be equilibrated in the conditions of relative humidity and temperature at which they will serve, rather than to specify moisture content at time of application. Figure 8-19 indicates the rate at which ⅛- and ¼-inch hardboards change moisture content at three relative humidities.

Readers wishing to further study wood moisture content, temperature, and humidity relationships are referred to Wengert (1976) and to the proceedings of a 1969 symposium on this subject; see Rosen et al. (1969).

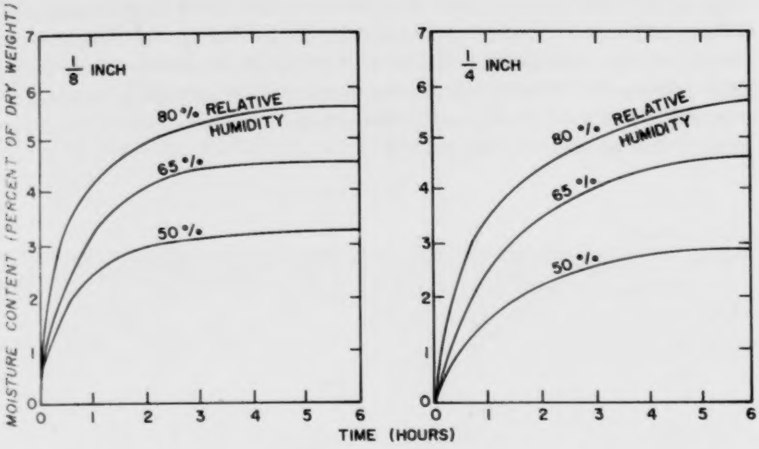

Figure 8-19.—Moisture content increase in ⅛-inch (left) and ¼-inch (right) ovendry Douglas-fir hardboard related to duration of exposure in 140°F air at three relative humidities. (Drawings after Kruse 1954.)

8-4 SHRINKING AND SWELLING

As hardwood dries from fiber saturation to ovendry, it shrinks in external dimensions; conversely, when dry wood is wetted, it swells. Because hardwood products sometimes do not shrink uniformly throughout their length and cross section, they may check and warp when moisture content changes. Some knowledge of the cause of shrinkage and the nature of its variation can contribute to successful wood use.

NORMAL SHRINKAGE

Water is adsorbed in hydrate form or as a monolayer of water molecules at polar sites in the non-crystalline regions where the long threadlike cellulose molecules are imperfectly oriented. Also, water is adsorbed as polymolecular water held in solid solution on the surface of the cellulose crystallites or as multilayers on the first-formed monolayer. In zones of low crystallinity, water may also be adsorbed onto hemicellulose molecules surrounding elementary fibrils. When wood dries as water evaporates, resulting surface tension forces between water and cellulose tend to draw the imperfectly aligned cellulose molecules of the less crystalline regions into closer proximity and more nearly parallel orientation (Campbell 1933).

On drying, cell walls diminish in thickness, while lumens appear to change but little in diameter. Therefore, the external radial and tangential dimensions of a block of wood must diminish as it dries. If the lumen diameters do not change, it also follows that volumetric shrinkage of a piece of wood during unrestrained ovendrying should be about equal to the volume of water adsorbed by the cell walls at fiber saturation (Stamm 1935).

COLLAPSE

During accelerated drying, some hardwoods develop an abnormal shrinkage termed **collapse** in which aggregations of cells are crushed so that lumen size diminishes and cell walls buckle (fig. 8-20). Unlike normal shrinkage, collapse occurs above the fiber saturation point. It is attributed to two causes: (1) tension stresses from capillary forces occasioned by withdrawing water from completely water filled lumens surrounded by impervious cell walls (Tiemann 1951), and (2) compressive forces developed in interior regions resulting from early shrinkage of outer regions (Stamm 1964, p. 226).

Hart (1970) and Hart and Darwin (1971) concluded that white oak contains free water in lumens of completely saturated, highly imperforate cells; never-dried mockernut hickory was also found to have water trapped in completely filled longitudinal and radial parenchyma cells (Hart et al. 1974). These findings support Tiemann's theory of collapse produced by capillary tension.

On the theory that lowered surface tension of liquid in wood should reduce capillary forces, Ellwood and Ecklund (1963ab) and Ellwood et al. (1963) exchanged water in collapse-prone wood with neutral organic liquids miscible in water and having low surface tension, e.g., ethylene glycol monoethyl ether, methanol, ethanol, and n-propyl alcohol. After such exchange, even severe drying conditions did not cause collapse. Organic liquids that were either basic or acidic, however, caused an increase in collapse because of wood deterioration.

In drying northern red oak by this procedure, Chech (1968) found no consistent differences in effects between n-propyl and ethyl alcohol, and observed that extreme checking and collapse under ovendrying conditions could be avoided in small specimens if water in the wood was replaced prior to drying by 70-percent alcohol concentrations. Minimum total shrinkage after ovendrying was achieved with 100-percent alcohol concentration.

In an extension of this work, Chen (1973), displaced water in small dowels of northern red oak by solvent replacement under pressure. Solvents used in series were methyl alcohol, followed by acetone, followed by pentane. In northern red oak, such water replacement permitted a 72-percent reduction in drying time without incurring collapse. The treatment also reduced normal volumetric shrinkage by 45 percent.

Collapse is most frequently associated with old-growth heartwood from trees grown on wet sites. Of hardwoods growing on southern pine sites, heartwood of sweetgum is perhaps the most prone to collapse. Frequently associated with collapse is the defect termed **honeycomb,** an internal void caused by tensile failure across the grain—usually in wood rays (fig. 8-20). Hardwoods that frequently develop honecomb during drying include all of the oaks as well as sweetgum.

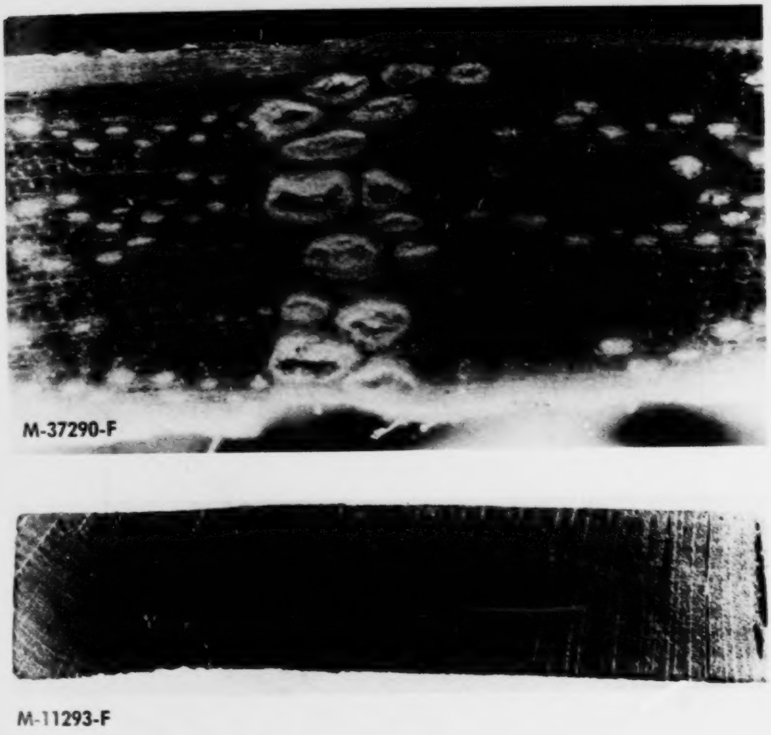

Figure 8-20.—(Top) Vessels in collapsed oak are deformed from natural near-circular shape to flat ellipsoidal shape, and board thickness is reduced. (Bottom) Honeycombing in oak opens voids caused by tensile stresses across the grain. (Photos from U.S. Forest Products Laboratory.)

FACTORS AFFECTING NORMAL SHRINKAGE

External dimensional changes during desorption or adsorption are usually expressed as a percentage of the swollen or green dimension.

$$\text{Shrinkage, percent} = \frac{\text{change in dimension from swollen size}}{\text{swollen dimension}}(100) \qquad (8\text{-}2)$$

Hardwood shrinks more tangentially than radially; longitudinal shrinkage in normal wood is usually slight. While volumetric shrinkage of hardwood dried from fiber saturation to ovendry varies considerably, it is commonly in the range from 12 to 20 percent (tables 8-9 and 8-10).

The percent shrinkage observed between green and ovendry conditions is correlated with species, specific gravity, extractive content and chemical constituents, fiber morphology, degree of restraint, and specimen temperature history. As noted previously, shrinkage begins at fiber saturation point and is approximately linearly correlated with moisture content between fiber saturation and ovendry condition; linearity of the correlation is imperfect, however, and empirically derived data result in curves that vary substantially with the factors noted above (fig. 8-21).

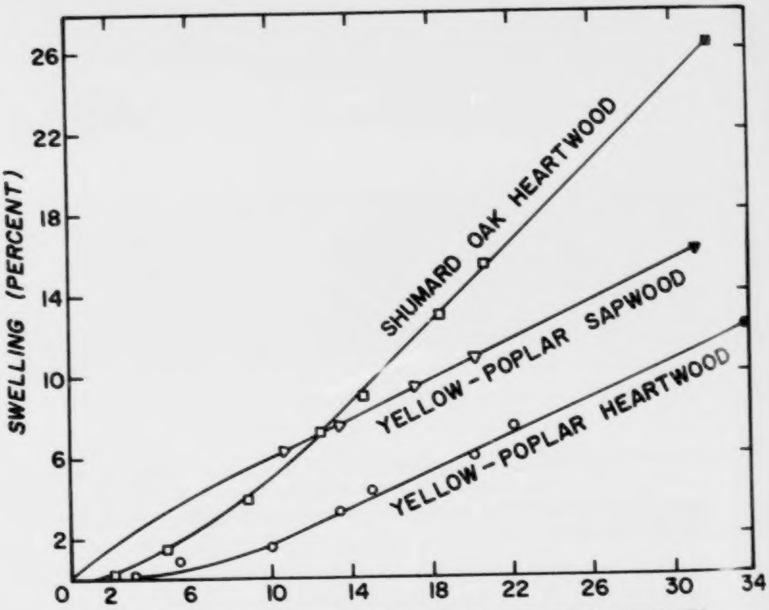

Figure 8-21.—Relationship between moisture content and percent volumetric swelling at 27°C of once-dried Shumard oak and yellow-poplar. The dark terminal symbols indicate fiber saturation points. (Drawing after Rosen 1974.)

TABLE 8–9.—*Shrinkage from green to ovendry moisture content of stemwood of sawlog-size trees of 22 hardwoods commonly associated with southern pine* (U.S. Department of Agriculture, Forest Service 1974, p. 3–9)[1]

Species	Radial	Tangential	Volumetric
	Percent		
Ash, green	4.6	7.1	12.5
Ash, white	4.9	7.8	13.3
Elm, American	4.2	7.2	14.6
Elm, winged	5.3	11.6	17.7
Hackberry	4.8	8.9	13.8
Hickory, bitternut	4.9	8.9	13.6
Hickory, mockernut	7.7	11.0	17.8
Hickory, pignut	7.2	11.5	17.9
Hickory, shagbark	7.0	10.5	16.7
Maple, red	4.0	8.2	12.6
Oak, black	4.4	11.1	15.1
Oak, chestnut	5.3	10.8	16.4
Oak, laurel	4.0	9.9	19.0
Oak, northern red	4.0	8.6	13.7
Oak, post	5.4	9.8	16.2
Oak, scarlet	4.4	10.8	14.7
Oak, southern red	4.7	11.3	16.1
Oak, water	4.4	9.8	16.1
Oak, white	5.6	10.5	16.3
Sweetgum	5.3	10.2	15.8
Tupelo, black	5.1	8.7	14.4
Yellow-poplar	4.6	8.2	12.7
Average	5.1	9.7	15.3

[1] Expressed as a percentage of the green dimension.

TABLE 8–10.—*Average values of radial and tangential shrinkage (saturated to ovendry) and specific gravity in sapwood and corewood of stemwood sampled 6 feet above ground in pine-site hardwood trees measuring 6 inches dbh* (Choong and Manwiller 1976)[1,2,3]

	Sapwood			Corewood[4]			Combined		
Species	Specific gravity	Radial shrinkage	Tangential shrinking	Specific gravity	Radial shrinkage	Tangential shrinkage	Radial shrinkage	Tangential shrinkage	Volumetric shrinkage[5]
		Percent			Percent			Percent	
Ash, green	0.561	5.5	8.6	0.555	5.7	8.8	5.6	8.7	14.3
Ash, white	.642	6.1	9.2	.631	6.0	8.9	6.1	9.1	15.2
Elm, American	.538	5.1	10.5	.532	6.0	11.1	5.5	10.8	16.3
Elm, winged	.642	5.2	10.2	.640	5.3	9.9	5.2	10.0	15.2
Hackberry	.536	4.5	9.3	.525	4.8	9.5	4.5	9.4	13.9
Hickory	.791	8.0	12.2	.786	7.9	12.1	8.0	12.2	20.2
Maple, red	.602	4.2	8.8	.578	4.5	9.2	4.5	9.1	13.6
Oak, black	.666	5.1	10.8	.657	5.2	11.1	5.1	10.7	15.8
Oak, blackjack	.694	4.4	8.8	.676	7.4	9.9	5.9	9.4	15.3
Oak, cherrybark	.646	5.2	11.2	.632	5.2	11.7	5.2	11.5	16.7
Oak, chestnut	—	—	—	—	—	—	—	—	—
Oak, laurel	.613	4.4	10.7	.606	4.6	10.6	4.5	10.6	15.1
Oak, northern red	.652	4.7	10.8	.648	5.1	11.6	4.9	11.2	16.1
Oak, post	.718	6.1	10.2	.718	6.6	11.9	6.3	11.1	17.4
Oak, scarlet	.643	5.2	10.9	.627	5.1	12.3	5.2	11.6	16.8
Oak, Shumard	.788	4.8	11.0	.766	5.2	11.2	5.0	11.1	16.1
Oak, southern red	.634	5.6	11.0	.611	5.7	12.0	5.6	11.5	17.1

TABLE 8–10.—*Average values of radial and tangential shrinkage (saturated to ovendry) and specific gravity in sapwood and corewood of stemwood sampled 6 feet above ground in pine-site hardwood trees measuring 6 inches dbh* (Choong and Manwiller 1976)[1,2,3]—Continued

Species	Sapwood			Corewood[4]			Combined		
	Specific gravity	Radial shrinkage	Tangential shrinking	Specific gravity	Radial shrinkage	Tangential shrinkage	Radial shrinkage	Tangential shrinkage	Volumetric shrinkage[5]
		Percent			*Percent*			*Percent*	
Oak, water	.604	3.9	10.0	.593	4.3	11.0	4.1	10.5	14.6
Oak, white	.718	6.6	11.4	.713	7.1	12.6	6.8	12.0	18.8
Sweetbay	.435	4.2	7.8	.435	4.1	8.0	4.2	7.9	12.1
Sweetgum	.466	5.1	10.1	.469	5.2	10.5	5.2	10.3	15.5
Tupelo, black	.493	4.9	9.6	.490	5.4	11.3	5.2	10.4	15.6
Yellow-poplar	.398	4.6	8.3	.393	4.2	8.4	4.4	8.4	12.8

[1] Each value under sapwood and corewood is based on two observations (sometimes only one) from each of 10 trees. Exceptions are corewood of black tupelo for which only six trees were sampled, and blackjack oak corewood which represents nine trees.

[2] Shrinkage measurements were made on samples resoaked from air-dry condition; shrinkage is expressed as a percentage of green volume.

[3] Specific gravity values are based on unextracted ovendry weight and volume when green.

[4] Corewood was sampled from central portions of the stems adjacent to the pith, but was not necessarily heartwood.

[5] Not measured, but computed as the sum of radial and tangential shrinkage. (See equation 8-5.).

Species—The continuously changing ages and diameters of trees in species populations make it difficult to derive average shrinkage values truly representative of each species. Table 8-9 lists percent shrinkage data accumulated by the U.S. Forest Products Laboratory over many years; values, which are averages from wood of merchantable trees generally 12 inches and greater dbh over all sites, vary considerably, with minimum and maximums as follows:

Type shrinkage	Shrinkage from green to ovendry	
	Minimum	Maximum
	Percent (species)	
Radial	4.0 (red maple) (laurel oak) (northern red oak)	7.7 (mockernut hickory)
Tangential	7.1 (green ash)	11.6 (winged elm)
Volumetric	12.5 (green ash)	19.0 (laurel oak)

Percent volumetric shrinkage can be computed with close approximation (Skaar 1972) from radial (S_R), tangential (S_T), and longitudinal (S_L) percent shrinkage as follows:

$$S_V \doteq S_R + S_T + S_L - (0.01)(S_R)(S_T) \qquad (8\text{-}3)$$

Only limited longitudinal shrinkage data on the hardwoods of interest are available. Equation 8-3 can be used, however, to estimate longitudinal shrinkage, i.e.:

$$S_L \doteq S_V - S_R - S_T + (0.01)(S_R)(S_T)$$

From average values in table 8-9, average longtitudinal shrinkage of these woods is computed as about 1.0 percent.

This value is higher than the usually considered average (0.1 to 0.6 percent) by many wood technologists. Hann's (1969) data on five hardwoods showed that longitudinal shrinkage is variable within single boards with clear straight grain; longitudinal swelling during drying was not uncommon, especially during drying from green to equilibrium at 30- or 65-percent relative humidity. When ovendry, some specimens showed no longitudinal shrinkage from the green condition, while others decreased in length by one percent (fig. 8-22).

Species-average values specific to sapwood and corewood of 6-inch pine-site hardwoods are shown in table 8-10. Values in this table were determined from stemwood of trees (table 3-1) sampled 6 feet above ground.

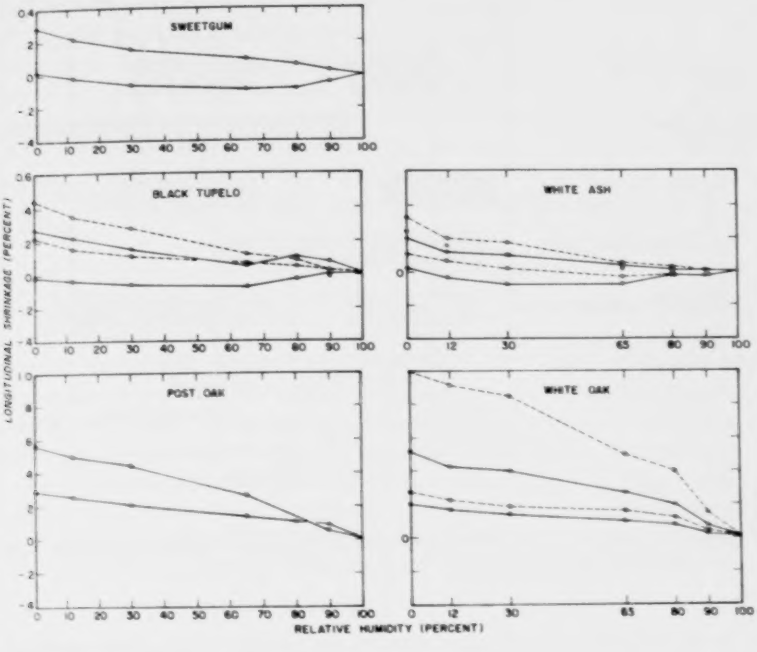

Figure 8-22.—Longitudinal shrinkage from green condition at 100-percent relative humidity to ovendry condition in five hardwood species. Solid lines represent maximum and minimum specimens cut from one board; dashed lines depict maximum and minimum specimens cut from a second board. (Drawings after Hann 1969.)

With the exception of white ash, green ash, and American elm, the average radial and tangential values agree closely with those presented in table 8-9. Figure 8-23 depicts the wide range of values within and among species. For corewood and sapwood samples combined (table 8-10) differences of 0.6 percent or more in radial shrinkage were significant. Radial shrinkage was least—4.1 to 4.5 percent—in water oak, sweetbay, yellow-poplar, red maple, laurel oak, and hackberry. It was greatest in hickory (8.0 percent), white oak (6.8), and post oak (6.3). White and post oak shrank more radially than did the nine red oaks.

In tangential shrinkage, differences of 0.8 percent or more were significant. Sweetbay, with 7.9 percent tangential shrinkage, displayed statistically less shrinkage than all species except yellow-poplar. The ashes, red maple, blackjack oak, and hackberry, ranging from 8.7 to 9.4 percent, were next lowest and not significantly different from each other. Hickory (12.2 percent), several oaks, and American elm (10.8) shrank most.

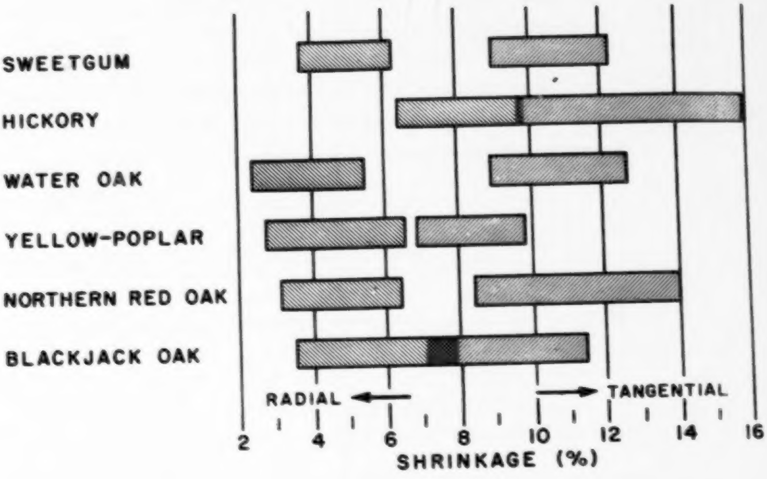

Figure 8-23.—Ranges of radial and tangential shrinkage values for representative species. (Drawing after Choong and Manwiller 1976.)

As seen from figure 8-21, the relationship between swelling and moisture content is not precisely linear; in shrinkage, however, the relationship with moisture content is nearly always a straight line (see fig. 8-5). Therefore, in the absence of exact information on a species, the shrinkage from fiber saturation point to any desired moisture content can be approximated on a linear basis, from data in table 8-4 and table 8-9 (for larger trees) or table 8-10 (6-inch trees):

$$S_m \doteq S_o \left(\frac{F_s - m}{F_s} \right) \tag{8-4}$$

where S_m is shrinkage (in percent) from the green condition to moisture content m, S_o is total shrinkage from green to ovendry (in percent) from table 8-9 or 8-10, and F_s is fiber saturation point for the species from table 8-4 (right-hand column).

Specific gravity—Hardwood of high specific gravity tends to have more radial, tangential, and volumetric shrinkage than that of low specific gravity.

One way of visualizing the relationship is to simplify equation 8-3 by assuming that the values for S_L and $(0.01)(S_R)(S_T)$ are both approximately 0.5, in which case they cancel each other in the equation, and volumetric shrinkage can then be expressed approximately as:

$$S_V \doteq S_R + S_T \tag{8-5}$$

Percent volumetric shrinkage, calculated by equation 8-5 from data in table 8-10, divided by wood specific gravity yields a number that averages 26.2 with range from 19.0 for blackjack oak sapwood to 34.1 for corewood from black tupelo. For these 22 species then, stemwood of 6-inch trees has volumetric shrinkage (green to ovendry) of about 26.2 times specific gravity.

To more accurately predict volumetric shrinkage from specific gravity, Choong and Manwiller (1976) computed from data in table 8-10 and from equation 8-4, a linear regression equation having a y-axis intercept of 7.4 as follows:

$$S_V \doteq 7.40 + (13.61)(\text{specific gravity}) \tag{8-6}$$

The correlation coefficient between apparent volumetric shrinkage and specific gravity was 0.78; i.e., 61 percent of the variation was attributable to variation in specific gravity.

In a study of second-growth white oak ranging from 0.610 to 0.649 in specific gravity, Paul (1969) found poor correlation between volumetric shrinkage and specific gravity, perhaps because of the limited range of the variables.

To express the relationship between longitudinal shrinkage (green to ovendry) and specific gravity (ovendry weight and volume when green) of five hardwood species, Hann (1969) computed linear regression equations for individual boards of each species as follows:

$$\text{Percent longitudinal shrinkage} = a + b\ (\text{specific gravity})$$

Resultant coefficients were as follows (5 to 16 specimens were analyzed from each board):

Species and board number	Equation coefficients a (intercept)	Equation coefficients b (slope)	Coefficient of correlation
Post oak			
1	1.17	−0.87	−0.60
White oak			
1	−3.55	5.44	.84
2	− .25	.83	.68
3	.05	.35	.12
Black tupelo			
1	.66	− .66	− .86
2	1.04	−1.35	− .81
3	.78	−1.01	− .76
Sweetgum			
1	− .39	.89	.11
White ash			
1	.85	−1.11	− .96
2	1.38	−1.71	− .96

Hann's data suggest that correlation between longitudinal shrinkage and specific gravity varies both within and between species and may be either positive or negative. Although Hann's data showed that white ash of high specific gravity had least longitudinal shrinkage, Koehler's (1931) results were less definite; when ovendry, medium-specific gravity white ash wood had zero longitudinal shrinkage while that of low specific gravity had 4.5 percent shrinkage; wood of high specific gravity was intermediate in shrinkage.

Extractives and chemical constituents—Hardwoods have less lignin and more hemicellulose than softwoods (Schroeder 1972, see also chapter 6), and their cell walls have slightly higher density (Kellogg and Wangaard 1969). Since volumetric shrinkage is usually correlated inversely with lignin content (Bosshard 1956, Boyd 1977), and positively with density and hemicellulose content, hardwoods shrink slightly more than softwoods.

As previously noted (section 8-2), woods with high extractive contents may have abnormally low fiber saturation points, and hence low bound water contents. Wood high in extractives thus shrinks less than comparable wood with low extractive content.

Transverse anisotropy—Hardwoods shrink more in the tangential direction than they do radially (tables 8-9, 8-10, and figs. 8-23, 8-24). This causes distortion in shape as hardwood dries. The nature of the distortion in a board, square, or round is dependent on the orientation of annual rings as viewed in cross section (fig. 8-25).

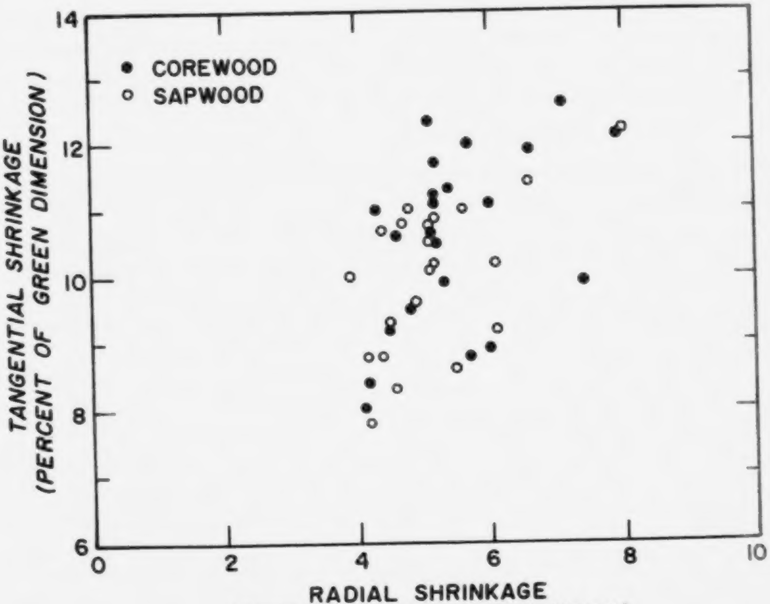

Figure 8-24.—Relationship between tangential and radial shrinkage in stemwood at 6-foot height in 22 species of hardwood trees measuring 6 inches dbh. Data from table 8-10.

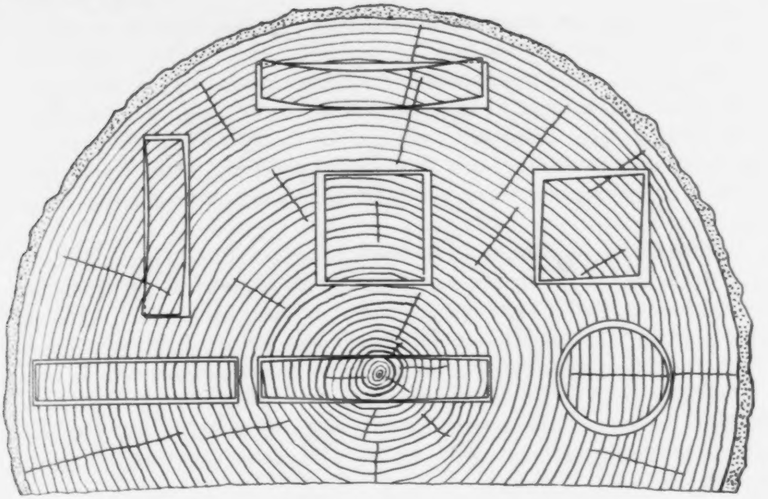

Figure 8-25.—Characteristic patterns of shrinkage and distortion for flats, squares, and rounds as affected by direction of the annual rings. (Drawing after Peck 1947.)

In ring porous hardwoods, tangential shrinkage and swelling are largely controlled by the latewood, since this tissue has less vessel volume and is therefore denser than earlywood; being denser, latewood shrinks more than earlywood and is sufficiently strong to force the earlywood to conform with its movement. Radial shrinkage and swelling, however, results from a summation of the contributions of earlywood and latewood, and is therefore less than tangential shrinkage and swelling.

The lamellar nature of wood explains only part of the transverse anisotropy in shrinkage of hardwoods, however. The low shrinkage of rays, and their high stiffness in the radial direction, further reduces radial shrinkage and swelling (Schniewind 1959).

In northern red oak, Morschauser (1954) observed that shrinkage of broad rays in the radial direction (green to ovendry) was only 2.5 percent; surrounding fiber tissue had radial shrinkage of 12.0 percent which compared closely with 14.0 percent tangential shrinkage in this tissue. Morschauser found that 2-inch blocks of northern red oak had radial shrinkage of 5.1 percent and tangential shrinkage of 8.5 percent; the difference was attributed to the restraint offered by rays to radial shrinkage.

McIntosh (1954, 1955, and 1957), measured shrinkage in earlywood and latewood of northern red oak, without broad rays, and found a tangential: radial shrinkage ratio for earlywood of about 2, while that for latewood was about 1. He suggested that restraint by fine ray tissue is responsible for the large T/R ratio of the relatively weak earlywood.

Tension wood and longitudinal shrinkage—Tension wood is prevalent in hardwoods (see sect. 5-7 and figs. 5-71 and 5-72). Boyd (1977), summarizing his work on eucalyptus species, concluded that in tension wood the absence of a restraining thick lignified S_2 layer permits substantial longitudinal shrinkage attributable to large microfibril angles in the S_1 layer of the cell wall; the galatinous layer in tension wood fibers apparently does not contribute significantly to longitudinal shrinkage, nor does it greatly impede longitudinal shrinkage of the S_1 layer.

Limited data on southern hardwoods have been published. Lassen and Cooper (1960) concluded that warp associated with tension wood in cuttings of southern red oak from southern Illinois was not serious. In white oak, however, Akins and Pillow (1950) found longitudinal shrinkage, which they attributed to gelatinous fibers, causing buckles and splits in veneer cut from tension wood.

Wahlgren (1957) related such shrinkage in overcup oak (*Quercus lyrata* Walt.) to numbers of gelatinous fibers and percentage of fibrous area present in stemwood tissues (fig. 8-26); in this study the maximum longitudinal shrinkage he observed was 0.9 percent.

Shrinkage data on American elm tension wood has been provided by Perem (1964) as follows:

Statistic	Tension wood	Normal wood
	Percent	
Longitudinal shrinkage	0.6	0.0
Volumetric shrinkage	13.6	15.8

Position in tree.—Since tension wood occurs in the upper side of leaning hardwood stems, specimens from the upper side of leaning trees will display more longitudinal shrinkage than those from the under side. While no data for pine-site hardwoods have been published, Schumann and Pillow (1969) found that 37 percent of 32-inch-long 5/8- by 1-1/8-inch cuttings sawn from the upper side of leaning stems of sugar maple (*Acer saccharum* Marsh.) shrank more than 1/32-inch when dried from 13- to 7-percent moisture content; only 7 percent cut from the lower side of leaning stems exceeded 1/32-inch longitudinal shrinkage.

Radial position in stem had no clear relationship to longitudinal shrinkage in white oak and white ash specimens studied by Hann (1969).

No data are published relating longitudinal shrinkage to height in stem.

Second-growth white oaks (50 to 80 years old) from seven localities in the Southern Appalachians showed no consistent shrinkage variation from outermost circumference to the center of the trees, and the range of variation was small. In these second-growth white oaks, wood having the highest volumetric shrinkage (24 percent) came from lowest stem sections, i.e., within one foot of the top of the stump (Paul 1939).

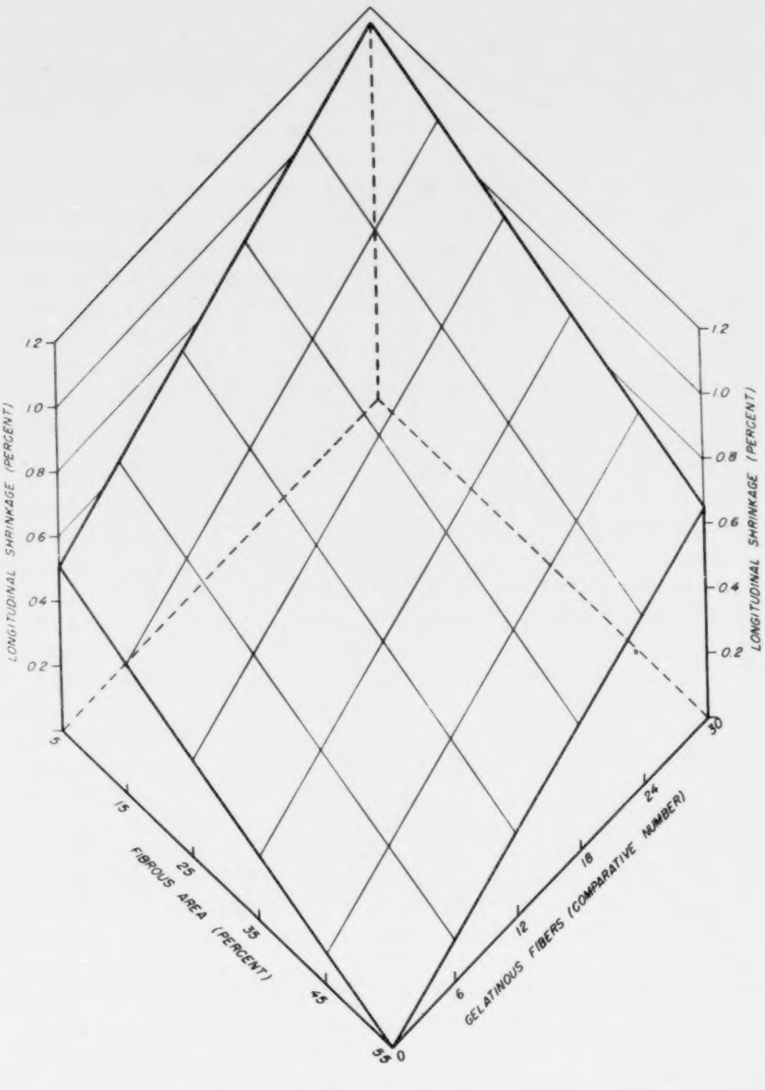

Figure 8-26.—Effects of gelatinous fibers and percentage of fibrous area on longitudinal shrinkage (green to ovendry) of overcup oak. (Drawing after Wahlgren 1957.)

In white oaks 230 to 290 years old, Paul (1939) found that volumetric shrinkage was least (15 percent or less) in outermost sapwood; progressively toward the pith were zones with 15 to 18 percent, 18 to 21 percent, and 21 to 24 percent, and a central cone about 9 inches in diameter at ground level with 24 to 30 percent (fig. 8-27). These variations are possibly attributable to a decrease in specific gravity with distance from the pith of these old-growth white oaks (see fig. 7-22, right).

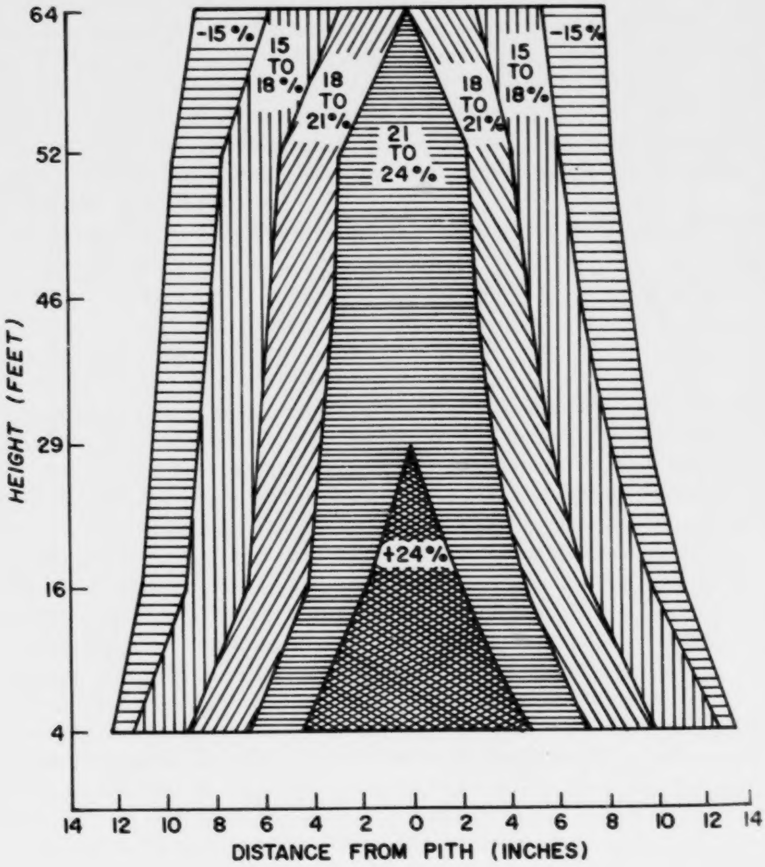

Figure 8-27.—Radial and vertical variation in percent of volumetric shrinkage (green to ovendry) in stemwood of five white oak trees from the Cumberland mountains averaging 29 inches dbh and ranging from 230 to 290 years old. Variations in shrinkage were probably correlated with specific gravity variations in these old-growth trees. (Drawing after Paul 1939.)

Water oak from the Mississippi Delta had only minor variations in volumetric shrinkage with height in the stem; in green ash, however, volumetric shrinkage was least in the lighter buttressed stem section (Paul and Marts 1934).

At 6-foot height in the 6-inch hardwoods (table 8-10) studied by Choong and Manwiller (1976), specific gravity tended to be lower—and shrinkage accordingly less—in corewood than in sapwood. In white oak, American elm, and blackjack oak, however, corewood shrinkage significantly exceeded that of sapwood in both the radial and tangential directions. It was greater in the tangential direction only in black tupelo, water oak, southern red oak, black oak, scarlet oak, and northern red oak. Reasons for these exceptions are now known; visual inspection of the samples revealed no evidence of collapse. Erickson (1949) indicated that wood near the pith of yellow-poplar samples shrank more than would be expected from the normal relation of shrinkage to specific gravity.

Restraint.—When wood is externally restrained during swelling, the lumens are reduced in size as the cell walls get thicker; on redrying to the original moisture content, it shrinks permanently to a smaller volume. If the wood is then restrained to the smaller dimension, reswollen and redried, it will shrink to a yet smaller dimension.

No information specific to southern hardwoods has been published. However, data on other species (Kollmann and Côté 1968, p. 215) indicate that repeatedly restraining wood in the radial direction through a series of wetting and drying cycles will finally result in more than 60 percent shrinkage in the radial direction; this radial shrinkage will be accompanied by a tangential swelling of about 35 percent. If the restraint is applied tangentially, the final tangential shrinkage will be in excess of 50 percent and will be accompanied by a radial swelling of about 25 percent.

Hoadley (1969) swelled 1-inch-diameter disks, measuring ¼-inch along the grain of American elm, hickory, northern red oak, and yellow-poplar while holding them under restraint within steel rings; in some cases concentrated deformation in the form of surface crushing accounted for a considerable amount of the total transverse set.

When green northern red oak wafers measuring 0.1 inch along the grain, 3.25 inches tangentially, and 1 inch radially were clamped to restrain tangential shrinkage, maximum force to restrain shrinkage decreased with increasing temperature and equilibrium moisture content conditions. Green oak wafters subjected to an atmosphere of 4-percent e.m.c. conditions at 85°F suffered tension failures at or within a large ray at approximately 35-percent moisture content. Aspen (*Populus tremuloides* Michx.), however, suffered no fractures when similarly dried under such restraint (Kass 1965).

Readers needing an approximation of swelling pressures resulting from confining dry hickory, northern red oak, and white ash dowels inside steel rings, and then swelling them, will find Bello's (1968) data useful.

Temperature history.—Shrinkage of oak during the drying process is increased if the green wood is initially steamed or dried at high temperature. Some excessive shrinkage can be recovered by heating (at 95°C) oak held at 12-percent moisture content. During carbonization wood shrinks substantially from the ovendry dimensions of uncarbonized wood. Summaries of experiments suggesting these conclusions follow.

McMillen (1955) measured width shrinkage of flat-sawn heartwood 2-inch-thick by 7-inch-wide boards cut from second logs of 110-year-old northern red oak having 7 to 10 rings per inch; green boards of 80- to 87-percent moisture content and specific gravity of 0.51 to 0.60 were dried at a range of dry-bulb temperatures to yield long and short drying times. Width shrinkage of the drying boards, measured at mid-thickness, was found to be positively correlated with drying temperature; that is, boards dried at the highest temperatures shrank most in width. For example, wood dried at 80°F to 10-percent moisture content had width shrinkage of 4.1 percent while matched boards dried at 140°F had nearly 6.7-percent width shrinkage (fig. 8-28). Width shrinkage at mid thickness on 2-inch boards is increased by early shrinkage of outer layers that impose compressive forces across the grain.

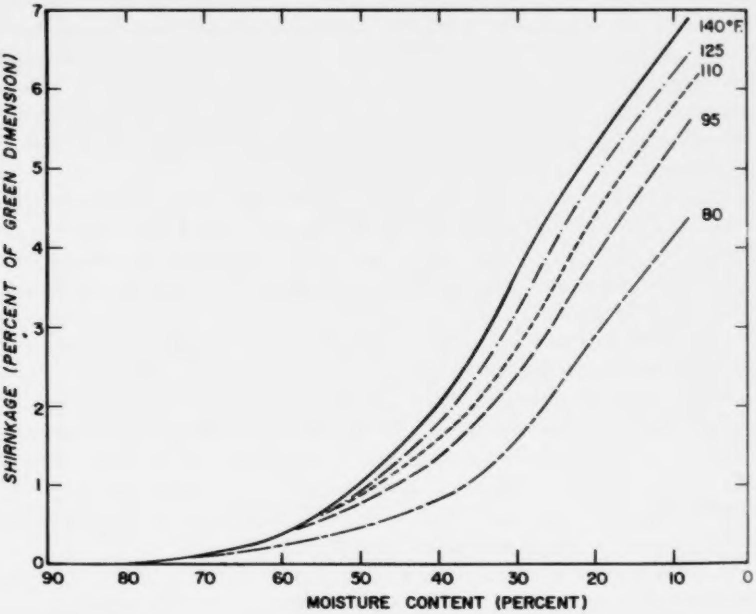

Figure 8-28.—Width shrinkage measured at mid thickness of 2- by 7-inch flat-sawn heartwood boards of northern red oak dried at different temperatures, related to average moisture content of the whole boards. During the first 6 to 16 hours of drying, wet-bulb temperature was set for an e.m.c. of about 18 percent; during the rest of the drying cycle (96 hours at 80°F, 56 hours at 110°F, 45 hours at 125°F, or 29 hours at 140°F), the wet-bulb temperature was gradually reduced to yield an e.m.c. condition of 2 to 4 percent at conclusion of drying (Drawing after McMillen 1955.)

Schniewind and Kersavage (1962) evaluated shrinkage in 1-inch square wafers of California black oak (*Quercus kelloggii* Newb.) measuring 1/16-inch along the grain. In these unextracted wafers, tangential and radial shrinkage were significantly greater when rate of drying was decreased and when the dry-bulb temperature was increased from 70°F to 140°F, as follows:

Drying rate and shrinkage direction	Dry-bulb temperature	
	70°F	140°F
Slow drying		
Radial	3.0	3.7
Tangential	7.9	12.9
Fast drying		
Radial	3.0	2.9
Tangential	7.2	9.3

In experiments with green beech (*Fagus sylvatica* L.), Stevens (1963) found that abnormally high shrinkage occurred in specimens dried slowly at high temperatures (i.e., with high wet-bulb temperatures as well as with high dry-bulb temperatures); those dried rapidly at high temperatures (i.e., with large wet-bulb depression) had least shrinkage.

Kubinsky (1971) observed shrinkage after drying of 20 mm cubes of northern red oak steamed for 6 hours and 96 hours at atmospheric pressure, and of unsteamed controls. He concluded that steaming of fresh-cut northern red oak increases linear and volumetric shrinkage and slightly reduces e.m.c. Prolonged steaming (96 hours) causes collapse despite careful drying. The increased shrinkage is caused by increased internal swelling (fig. 8-29); it is probably made possible by increased permeability (from action of acetic acid formed during steaming) of the warty layer and accessibility of the S_3 layer through the empty lumina. From subsequent experiments with 24 mm cubes, Kubinsky and Ifju (1974) related steaming time to volumetric, tangential, and radial shrinkage (fig. 8-30). They concluded that northern red oak should not be exposed to steaming at atmospheric pressure for periods longer than 24 hours.

Under some circumstances, excessive shrinkage can be recovered. Kubler (1970) cut plugs 19 mm in diameter perpendicular to the faces of 37-mm-thick green flatsawn and quartersawn northern red oak boards. When these plugs were dried from green condition at 90-percent, then 80-percent, and finally 65-percent relative humidity (the last at 27°C) to 12-percent e.m.c., they had abnormally high shrinkage averaging 17 percent tangentially and 7.2 percent radially. When the plugs were held at 12-percent e.m.c. conditions, but the dry-bulb temperature raised to 95°C, 40 to 60 percent of the excessive shrinkage was recovered. Kubler concluded that recovery of this magnitude will only occur if specimens are maintained at 12- to 20-percent moisture content while undergoing the heat treatment.

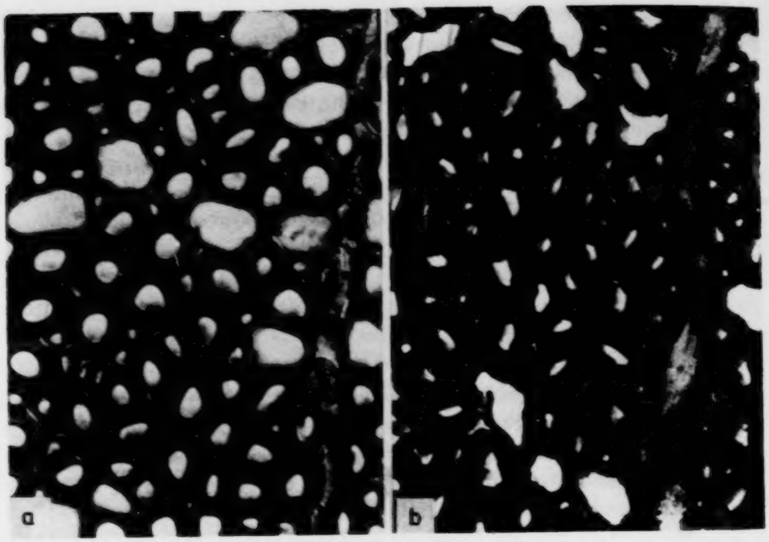

Figure 8-29.—(Left) Cross section of latewood fibers of unsteamed northern red oak. (Right) Lumina of reduced size caused by internal swelling of cell walls in matched specimens steamed for 36 hours. (Micrograph from Kubinsky 1971.)

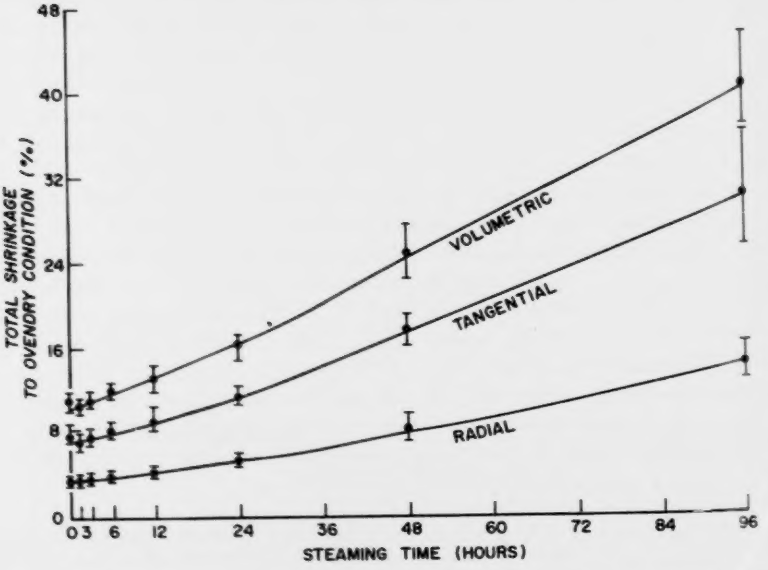

Figure 8-30.—Influence of steaming time at atmospheric pressure on total shrinkage (green to ovendry) of 24 mm cubes of northern red oak with unextracted specific gravity of 0.52 based on ovendry weight and volume when green. (Drawing after Kubinsky and Ifju 1974.)

Extreme heating of wood in the absence of oxygen causes carbonization; if carbonized at 600°C, dry weight loss is about 80 percent. Shrinkage of wood during carbonization, from ovendry dimensions, is substantial; wood carbonized at 600°C shrinks more than that carbonized at 400°C (table 8-11).

TABLE 8–11.—*Shrinkage of yellow-poplar and white oak wood during carbonization expressed as a percentage of dimensions of parent ovendry wood before carbonization* (Beall et al. 1974)

Species and carbonizing temperature (°C)	Longitudinal	Radial	Tangential
	Percent		
Yellow-poplar			
400	13.3	26.4	31.3
600	18.5	29.1	35.1
White oak[1]			
277 to 400	11.4	15.5	25.7

[1] Data for white oak are from McGinnes et al. (1971).

SWELLING IN NON-AQUEOUS LIQUIDS

Swelling of wood in liquids other than water is of interest to wood technologists. Rosen (1978) exposed unextracted once-dried 3.8-cm-square wafers of black oak and yellow-poplar measuring 3mm along the grain to vapor (for 2 weeks) and liquid (for 5 hours) of normal alcohols, branched alcohols, and organic acids. With these chemicals, swelling decreased as molecular weight of the acids and alcohols increased; branched alcohols yielded less swelling than normal straight-chained alcohols (table 8-12). An additional 42-day liquid soak beyond the 14-day vapor and 5-hour liquid exposure caused additional swelling of the wood with most of the chemicals used by Rosen.

Petroleum oils and creosote do not swell wood.

SWELLING OF RECONSTITUTED PRODUCTS

As noted in section 8-3, the equilibrium moisture contents of reconstituted wood products are generally lower than those of solid woods, and differ according to product. Shrinking and swelling characteristics of such products also vary substantially according to manufacturing process. Details of the swelling properties of fiberboards can be found in chapter 23. Similar information on flakeboards and composites is in chapter 24.

TABLE 8–12.—*Volumetric swelling, relative to swelling in water, and fiber saturation point of unextracted, once-dried black oak and yellow-poplar in eight normal alcohols, six branched alcohols, and eight organic acids* (Rosen 1978)[1]

Chemical	Black oak		Yellow-poplar	
	Relative swelling[2]	Fiber saturation point[3]	Relative swelling[2]	Fiber saturation point[3]
	Percent		*Percent*	
Normal alcohols				
Methanol	0.95	24.1	0.97	24.6
Ethanol	.64	15.8	.78	18.9
Propanol	.51	13.8	.69	18.1
Butanol	.13	4.9	.57	13.9
Pentanol	.03	—	.21	6.3
Hexanol	.02	—	.04	—
Heptanol	.02	—	.03	—
Octanol	.03	—	.03	—
Branched alcohols				
i-propanol	.38	11.0	.63	17.1
2-butanol	.10	4.6	.54	13.5
i-butanol	.04	—	.10	2.7
t-butanol	.03	—	.05	—
2-pentanol	.03	—	.10	3.1
i-pentanol	.03	—	.05	—
Acids				
Formic	1.45	64.8	1.28	63.3
Acetic	.95	28.9	1.07	36.2
Propionic	.43	13.4	.76	22.3
Butyric	.05	—	.28	10.2
Valeric	.02	—	.03	—
Hexanoic	.03	—	.02	—
Heptanoic	.01	—	.02	—
Octanoic	.01	—	.01	—
Water	1.00	29.4	1.00	31.5

[1] Swelling of black oak in water was 17.6 percent, that of yellow-poplar 14.7 percent.

[2] After 14-day exposure to the chemical's vapor followed by 5-hour immersion in the liquid chemical.

[3] Chemical adsorbed by wood from vapor only, as percent of ovendry weight.

TREATMENTS TO INHIBIT SHRINKING AND SWELLING

Dimensional stability of wood can be improved by applications of heat and pressure, exposure to radiation, and impregnation with plastics or chemical reagents (see fig. 21-12 and related discussion). The ease of impregnation with plastics or chemical reagents differs widely among southern hardwood species; in general they are more difficult to impregnate than sapwood of southern pine because of differences in pit membrane structure (see section 8-6 and chapter 21).

A review of stabilizing processes can be found in Agriculture Handbook 420, pages 1128-1143 (Koch 1972). Some recent additions to the literature on stabilization of solid wood products include the following:

Citation	Subject
Banks(1973)	Water uptake by Scots pine sapwood, and its restriction by the use of water repellants
Bower and Wellons (1974)	Sorption of styrene and acrylonitrile by wood aerogels
Burmeister and Wille (1976)	Changes in cell-wall structure caused by heat treatment
Ellwood et al. (1972)	Dimensional stabilization of wood with vinyl monomers
Furuno and Goto (1974)	The penetration of polyethelene glycol into woody cell wall
Hallock and Bulgrin (1972)	Stabilization of hard maple flooring with polyethylene glycol 1000
Merz and Cooper (1968)	Effect of polyethylene glycol on stabilization of black oak blocks
Rosen (1975)	High pressure penetration of dry hardwoods
Rowell (1977)	Effects of drying method and penetration of chemicals on chemically modified southern pine wood
Rowell and Gutzmer (1975)	Chemical modification of wood: reactions of alkylene oxides with southern yellow pine
Rowell et al. (1976)	Effects of alkylene oxide treatments on dimensional stability of wood
Siau (1969)	The swelling of basswood by vinyl monomers
Siau and Meyer (1966)	Comparison of the properties of heat and radiation cured wood polymer combinations
Siau et al. (1978)	Wood polymer composites from southern hardwoods
Stamm (1974)	Dimensional stabilization of wood with water soluble fire retardant bulking chemicals compared to polyethelene glycol-1,000

8-5 HEAT OF SORPTION

When wood adsorbs water, heat is evolved. The amount of heat given off when 1 g of ovendry wood is immersed in sufficient liquid water to bring the wood to fiber saturation is defined as the **total integral heat of wetting.** The total integral heat of adsorption (from water in vapor form) is the total integral heat of wetting plus the heat of vaporization.

Stamm's (1964, p. 204) survey of the literature indicated a range among six species from 16.6 to 20.5 calories per gram total integral heat of wetting. This range includes some differences attributable to the temperature of observation and fineness of the wood as well as species differences. Finely divided wood gives off more heat than solid wood, and the amount of heat evolved is negatively correlated with the temperature of the wood.

Kajita's (1976) study of 38 hardwoods and softwoods indicated a range in total integral heat of wetting in water at 30°C from 12.4 to 20.4 calories per gram. He concluded that total integral heat of wetting decreases linearly with increasing water temperature, and that the slope coefficient is 0.076 calories/°C/g of wood. He found, also, that total integral heat of wetting of wood of a species is positively related to its equilibrium moisture content at 100 percent relative humidity and 30°C; i.e., (percent e.m.c.) (0.7) ≐ total integral heat of wetting. Percentage of holocellulose and alpha cellulose were positively correlated with total integral heat of wetting, but extractive content was negatively correlated. Sapwood and earylwood had slightly higher total integral heats of wetting than did heartwood and latewood.

Kajita et al. (1976) found that the total integral heat of wetting of alpha cellulose was almost the same as that of wood; of the materials tested, hemicellulose had the highest total heat of wetting. The proportional contributions to heat of wetting of the three components of extractive-free hardwood (*Fagus* spp.) were 0.36 for alpha cellulose, 0.48 for hemicellulose, and 0.16 for lignin.

Data specific to wood and bark from 6-inch hardwoods grown on southern pine sites (table 3-1) indicate that the total integral heat of wetting in water at 25°C is greatest for post oak wood (21.5 calories per gram) and least for winged elm wood (17.3) as shown in table 8-13.

Regression analysis correlating these heat of wetting data for wood to fiber saturation points determined from shrinkage of wood (table 8-4, fourth column) yields the following equation, which accounted for 55 percent of observed variation (i.e., $R^2 = 0.55$):

$$\text{Total integral heat of wetting, calories per gram} = 4.6441 + 0.4796\,(\text{fiber saturation point, percent}) \qquad (8\text{-}7)$$

TABLE 8-13.—*Total integral heats of wetting (and standard deviations) of wood and bark from stems of 6-inch hardwoods of 22 species grown on southern pine sites.*

Species	Wood[1]	Inner bark[1,2]	Outer bark[2]
	Calories per gram		
Ash, green	18.13 (0.71)	17.22 (0.66)	16.92
Ash, white	20.43 (0.52)	17.56 (0.30)	—
Elm, American	19.10 (0.60)	16.60 (0.79)	20.94
Elm, winged	17.27 (0.62)	15.04 (0.54)	15.29
Hackberry[3]	18.47 (0.71)	16.84 (0.55)	11.63
Hickory	20.50 (0.21)	19.09 (0.27)	18.23
Maple, red	18.93 (0.37)	17.80 (0.74)	15.29
Oak, black	19.99 (0.52)	17.14 (0.89)	—

TABLE 8-13.—*Total integral heats of wetting (and standard deviations) of wood and bark from stems of 6-inch hardwoods of 22 species grown on southern pine sites.—Continued*

Species	Wood[1]	Inner bark[1,2]	Outer bark[2]
	Calories per gram		
Oak, blackjack	18.33 (0.47)	20.01 (0.37)	—
Oak, cherrybark	18.84 (0.53)	16.53 (0.80)	—
Oak, laurel	18.62 (0.49)	19.08 (0.52)	—
Oak, northern red	19.96 (0.51)	20.45 (0.68)	—
Oak, post	21.49 (0.39)	14.16 (0.84)	—
Oak, scarlet	18.28 (0.52)	18.66 (0.07)	—
Oak, Shumard	18.83 (0.48)	17.60 (0.51)	—
Oak, southern red	19.37 (0.63)	19.29 (0.82)	20.98
Oak, water	18.24 (0.28)	17.98 (0.65)	—
Oak, white	20.42 (0.36)	18.63 (0.59)	12.12
Sweetbay	18.49 (0.29)	19.73 (0.32)	14.59
Sweetgum	20.81 (0.46)	18.28 (0.32)	15.72
Tupelo, black	18.81 (0.27)	17.76 (0.42)	—
Yellow-poplar	19.50 (0.19)	19.82 (0.37)	17.65

[1] Unpublished data in letter from Hiromu Kajita (Kyoto Prefectural University, Japan) to P. Koch dated February 23, 1978.

[2] Dated from Kajita 1975.

[3] Mostly sugarberry.

8-6 PERMEABILITY

The capacity of wood to allow passage of fluids under pressure is called its **permeability.** The mass movement of molecules under pressure is distinct from the random motion of single molecules during diffusion to equalize concentration (or partial pressure) gradients. Permeability is numerically expressed in units termed **Darcy** (after Darcy's law) that are equal to the flow (cm^3/sec) of a specified fluid through a cubical specimen measuring 1 cm on a side with a pressure gradient between surfaces through which the flow occurs of 1 atmosphere/cm multiplied by the fluids's viscosity in centipoises. The viscosity of water at 20°C is one centipoise; that of air at 18°C is 0.0183 centipoise.

Hardwoods from southern pine sites vary greatly in their permeability and these variations influence their uses. Oaks, for example, vary from white oak, so impermeable that barrels made from it store bourbon whiskey without leakage, to northern red oak which is permeable enough for easy pressure perservative treatment for use as fence or highway posts. Wood permeability controls penetration of pulping liquor into chips and influences the effectiveness of surface paints, stains, and water repellants. Kiln drying time is, in most cases, inversely proportional to permeabilty.

WOOD ANATOMY AND PERMEABILITY[1]

In the stemwood of most hardwoods, longitudinal fluid flow is primarily through the vessels; in others such as hickory, fiber tracheids play an important role. Vessel cells are perforated at their ends and when not blocked by tyloses (fig. 5-13) or extraneous materials, they provide continuous flow paths (fig. 5-52). Once fluid is in the vessels, flow can occur laterally through half-bordered and bordered pit pairs (fig. 8-31) into the adjoining elements, but usually not as freely as through end-wall perforations. The permeability of intervascular pit membranes in sapwood may be less in winter than in summer (Wheeler 1981).

Although fibers often constitute the bulk of hardwood tissues, their thick walls and small irregularly distributed pits usually make them less important than vessels in initial liquid penetration. Their permeability may, however, determine subsequent spread of fluid from the vessels. Although checks may occur in fiber walls during drying, the primary walls usually remain unruptured, the main avenues of flow from cell to cell being through pit membranes. The role of ray tissues in fluid penetration into southern hardwoods has been little explored, but in these tissues also pit structure is the major factor.

Pits, gaps left in the secondary wall of the cell and subtended by a modified primary wall which is the pit membrane, are described in section 5-6 and by figures 5-62 through 5-68.

Hardwood bordered pit-pairs resemble softwood bordered pit pairs, in that the pit membrane is overarched by prominent borders (fig. 8-31, top left and bottom). In hardwoods, however, the pit membranes do not incorporate a torus (central thickened portion) and appear in surface view to lack openings (fig. 8-31, right). Since fluid flow between vessels is known to occur through these membranes, their mirofibril arrangement probably resembles the structure of filter paper having no obvious openings, but still permitting fluid flow (fig. 8-31, top left and bottom). Ultra-fine pores left by the removal of plasmodesmata may also exist.

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[1] With some changes and additions, this subsection is from Thomas (1976) by permission of R.J. Thomas and the Society of Wood Science and Technology.

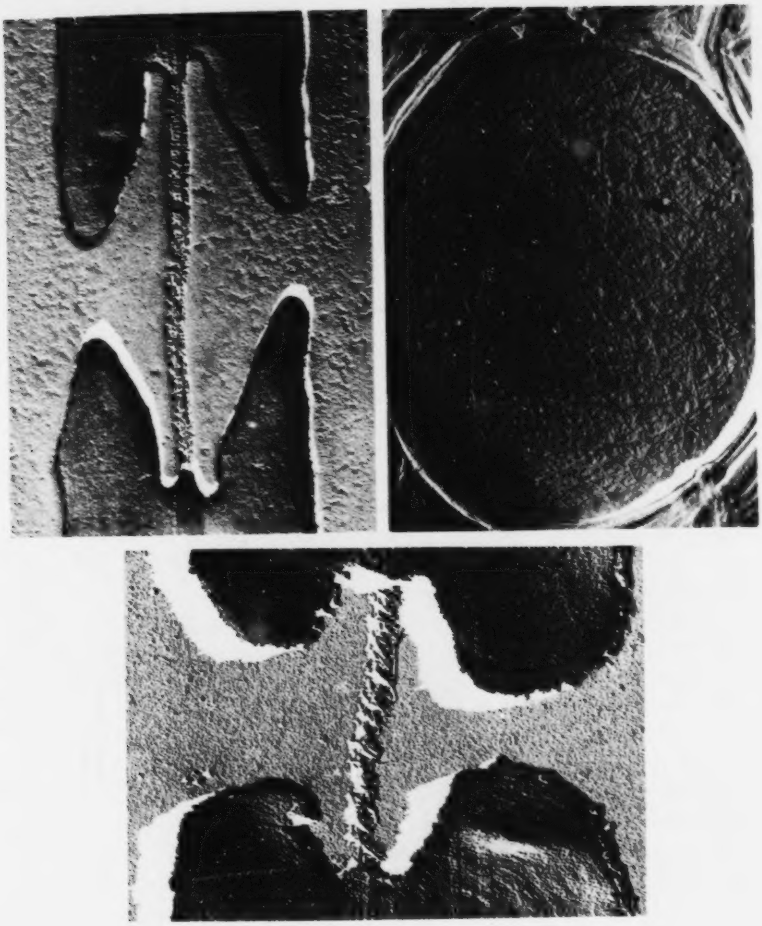

Figure 8-31.—Intervessel bordered pit-pairs in three southern hardwoods. (Top left) Cross-sectional view from sweetgum (13,000 X). (Top right) Surface view of pit membrane from black tupelo (15,000 X). (Bottom) Cross-sectional view from yellow-poplar (15,000 X). (Photos from files of R. J. Thomas.)

Examination of minute anatomy in heartwood of three hardwoods (one ring porous and two diffuse porous) illustrates the diversity of flow paths in hardwood species and the varying degree of flow obstructions.

Hickory.—Solitary vessels in hickory have as contiguous cells either ray or longitudinal parenchyma elements. Either ray or longitudinal parenchyma are adjacent to the radial wall; only the latter adjoin the tangential wall. Since vessels do not end in isolation, individual vessel elements occasionally border the tangential walls of other vessel elements. Individual vessels, as well as vessels in radial rows of two or three, are also completely surrounded by parenchyma. Therefore vessels, whether they are solitary or in radial rows of two or three, are isolated from fibers. As a result, pits in vessels lead either to other vessels or parenchyma cells.

In the hickories intervessel pit membranes from both the sapwood and heartwood zones may be thick and heavily encrusted (fig. 8-32ABC). In such wood, pit membranes showing the microfibril component are not observed unless encrustations are removed by treatment with sodium chlorite. The degummed membrane is thicker and the microfibril arrangement less porous than those in the sapwood of many hardwood species (compare figures 8-31 (top right) and 8-32C). Encrustations and thickened membranes considerably reduce flow between vessels.

Membranes in pit pairs connecting vessels to parenchyma cells consist of the primary walls of both cell types separated by a middle lamella. Material termed the protective layer is found on the parenchyma side of the membrane, and in hickory sapwood, on the vessel side there are encrustations called **gum,** secreted by the parenchyma cells (fig. 8-32D). Often the gum material lines vessel walls and fills intervessel pit canals, thus hindering the flow pathway from vessel to vessel (fig. 8-33A).

The lumens of hickory heartwood vessels contain many tyloses, lining the lumen walls, obstructing pit apertures, and sometimes filling and blocking the lumens. Figure 8-33B shows heartwood vessel-to-parenchyma pit-pairs with vessel pit chambers completely filled with gum and the pit apertures overlaid with tyloses. Such blockages virtually eliminate vessel-parenchyma and intervessel pit-pairs as conducting passageways.

Fiber tracheids, which constitute over one-half of the wood volume of hickory, are relatively thick-walled fibrous cells with pointed ends and bordered pits. Since fiber tracheids are not contiguous to vessels, their pit-pairs connect only to each other or to parenchyma. The pit pairs connecting fiber tracheids are bordered and possess a deep pit canal (fig. 8-33C). Pit pairs between fibers and parenchyma contain thick membranes which do not appear conducive to liquid flow.

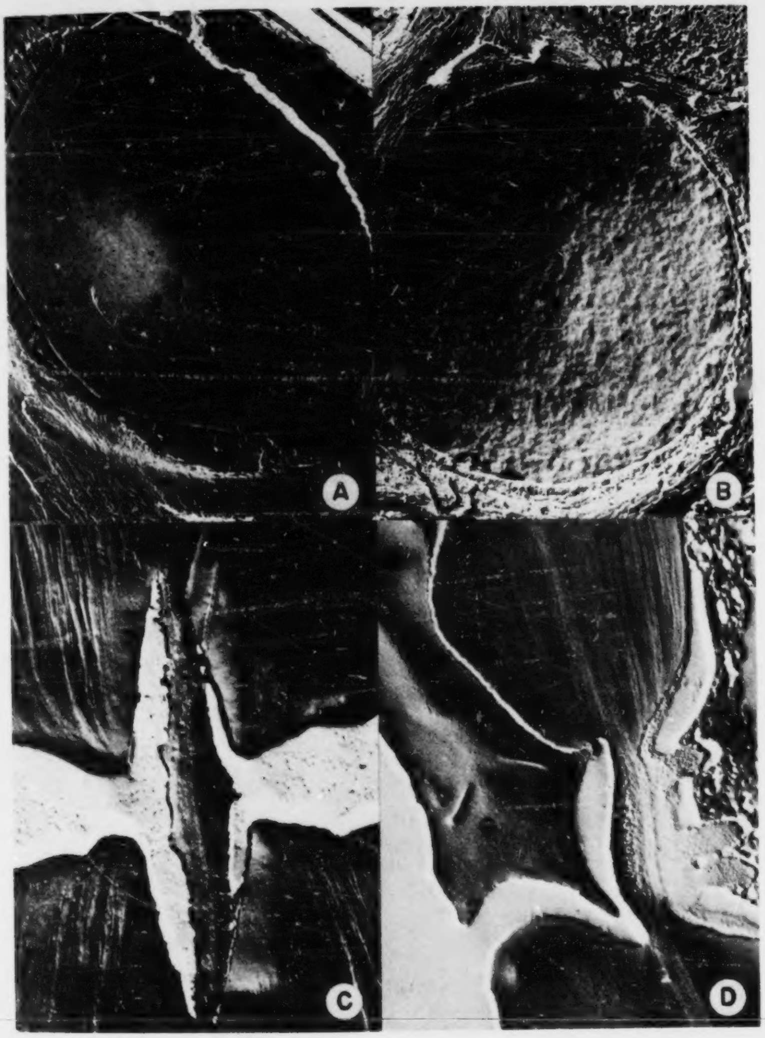

Figure 8-32.—(A) Typical heavily encrusted intervessel pit membrane found in the sapwood of mockernut hickory. 9,000X. (B) Encrusted intervessel pit membrane from the heartwood of mockernut hickory. 9,000X. (C) Cross-sectional view of portion of an intervessel pit-pair from the sapwood of mockernut hickory. Note the incrusted and thick pit membrane. 11,700X. (D) Vessel to parenchyma pit-pair from hickory sapwood showing a deposit of gum (G) in the vessel. Note also the fingerlike projections of the protective layer on the parenchyma side of the pit membrane. Gum was displaced from the pit membrane as a result of cutting stresses. 8,500X. (Photos from Thomas 1976.)

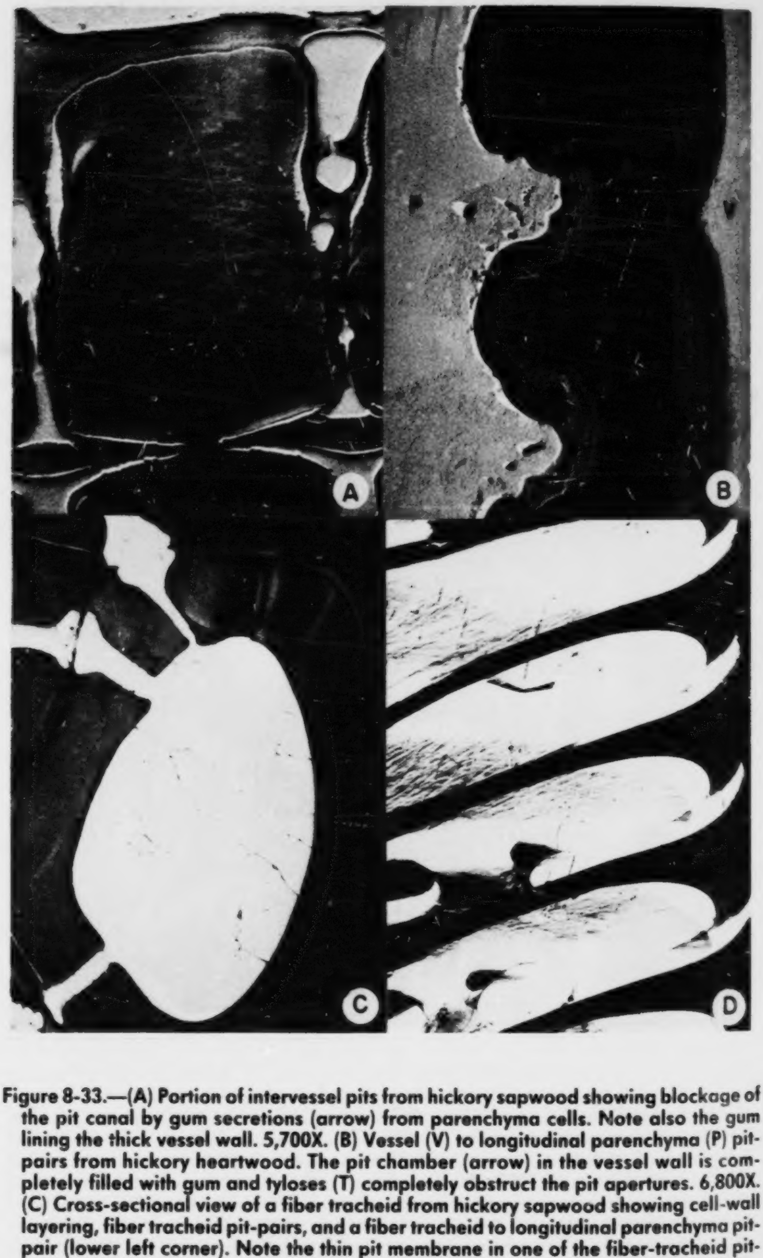

Figure 8-33.—(A) Portion of intervessel pits from hickory sapwood showing blockage of the pit canal by gum secretions (arrow) from parenchyma cells. Note also the gum lining the thick vessel wall. 5,700X. (B) Vessel (V) to longitudinal parenchyma (P) pit-pairs from hickory heartwood. The pit chamber (arrow) in the vessel wall is completely filled with gum and tyloses (T) completely obstruct the pit apertures. 6,800X. (C) Cross-sectional view of a fiber tracheid from hickory sapwood showing cell-wall layering, fiber tracheid pit-pairs, and a fiber tracheid to longitudinal parenchyma pit-pair (lower left corner). Note the thin pit membrane in one of the fiber-tracheid pit-pairs and its absence in the other pit-pair. 4,500X. (D) Part of a scalariform perforation plate from sweetgum sapwood. Revealed through the open perforations are vessel to ray parenchyma pits in the back wall of the vessel. 2,900X. (Photos from Thomas 1976.)

The membrane in pits between fiber tracheids is relatively thin as compared to intervessel pit membranes and is often disrupted or missing. Disrupted or missing pit membranes are possibly artifacts caused by methacrylate swelling during specimen preparation. If this is the case, the fact that intervessel or fiber-to-parenchyma pit membranes remained intact during specimen preparation emphasizes the tenuous nature of the interfiber pit membranes and the likelihood that they provide the liquid flow pathway. The foregoing characterizes interfiber pits of both the heartwood and sapwood, as encrustations are not deposited on the pit membranes in heartwood.

Although the vessels of hickory constitute a very small percentage of the wood volume and their pits are occuluded with tyloses and gum deposits, hickory is only moderately difficult to penetrate. This is possible because of longitudinal flow along the fiber tracheids (Gerry 1914; Teesdale and MacLean 1918) due to their thin pit membranes and the absence of encrustations on them.

Sweetgum.—Despite the fact that vessels occupy slightly over half of the wood volume, old-growth sweetgum heartwood is classified as very difficult to penetrate. In the sapwood, uninterrupted flow occurs between vessel elements, and thus along the vessel, through scalariform perforation plates, consisting of parallel openings separated by cell-wall material termed bars (fig. 8-33D). In heartwood, the perforation plate openings are completely obstructed by tyloses (fig. 8-34A) growing around the bars and across the openings, thus completely blocking free fluid flow along the vessel (fig. 8-34B). While only occasionally crossing the lumen, tyloses line vessel walls and block pits leading from vessels to adjacent cells. In heartwood, flow is also hindered by encrustations on intervessel pit membranes.

Microfibrils are clearly visible in membranes of pit-pairs interconnecting sapwood fibers (fig. 8-34C), and ultrathin sections reveal a rather thin membrane (fig. 8-35A). In the heartwood, heavy encrustations on the pit membranes obscure the microfibrils (compare fig. 8-34C and D), and membranes are substantially thicker (fig. 8-35B).

Such structural obstructions to liquid flow, deposited as sweetgum heartwood is formed, are responsible for its extreme resistance to liquid penetration.

Black tupelo.—Extractives are also deposited in the heartwood of black tupelo, but in amounts that do not completely block the flow paths. Figure 8-35CD depicts scalariform perforation plates with depositions which only partiably block the openings. This material, the identity of which is not known, was also found in the vicinity of intervessel pits partly obstructing the pit apertures, canals, and chambers. The interfiber pits contained relatively thick membranes without detectable openings, and many fibers contained depositions along lumen walls.

Since vessels constitute about one-half of the total volume and lack tyloses or depositions that completely block fluid flow pathways, the wood is easily penetrated with fluids.

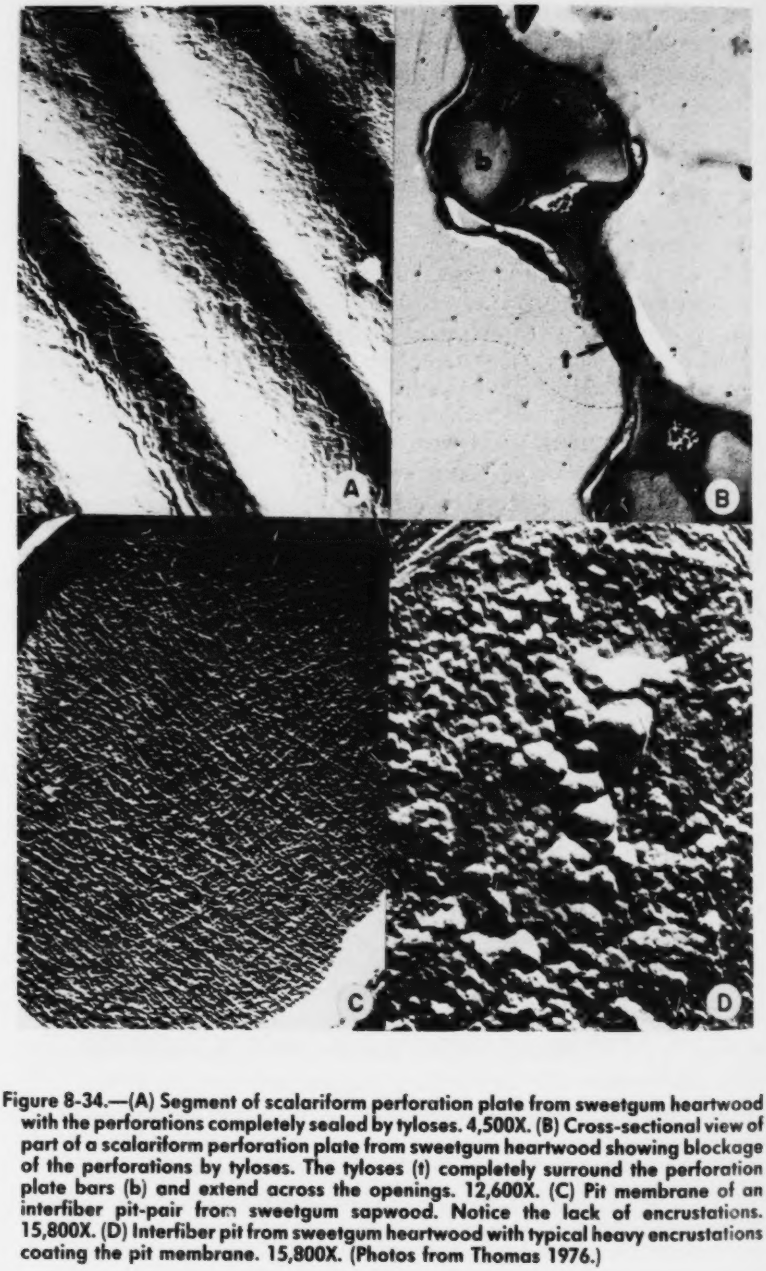

Figure 8-34.—(A) Segment of scalariform perforation plate from sweetgum heartwood with the perforations completely sealed by tyloses. 4,500X. (B) Cross-sectional view of part of a scalariform perforation plate from sweetgum heartwood showing blockage of the perforations by tyloses. The tyloses (t) completely surround the perforation plate bars (b) and extend across the openings. 12,600X. (C) Pit membrane of an interfiber pit-pair from sweetgum sapwood. Notice the lack of encrustations. 15,800X. (D) Interfiber pit from sweetgum heartwood with typical heavy encrustations coating the pit membrane. 15,800X. (Photos from Thomas 1976.)

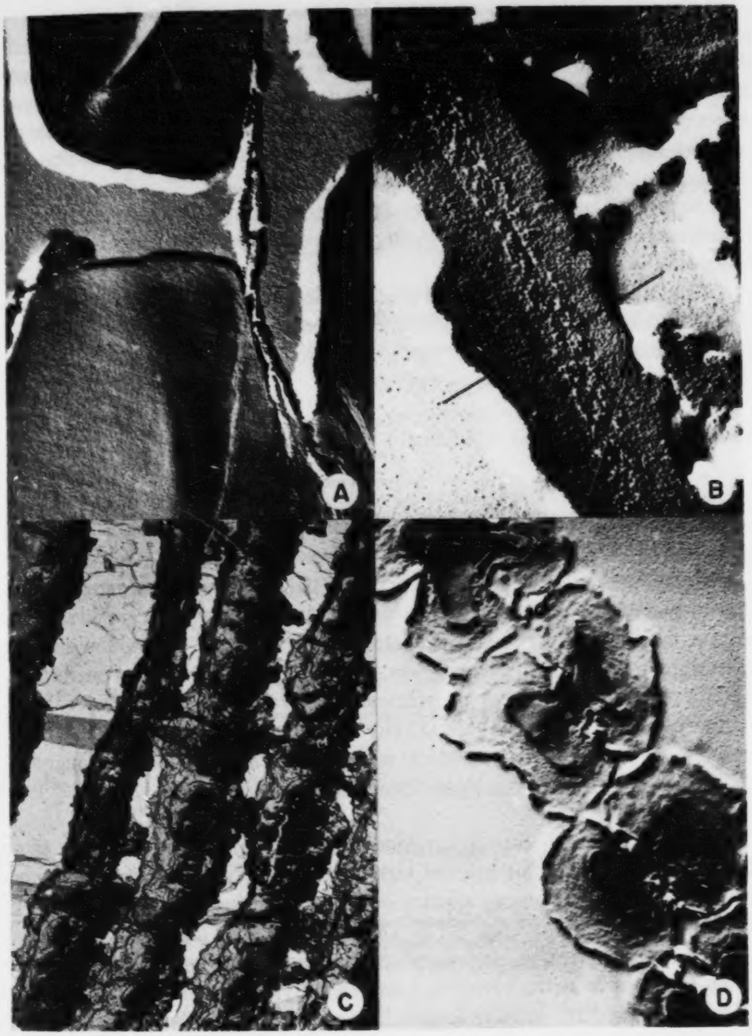

Figure 8-35.—(A) Cross-sectional view of an interfiber pit-pair from sweetgum sapwood. 15,800X. (B) Cross-sectional view of an encrusted interfiber pit membrane from sweetgum heartwood. Note the substantial increase in pit membrane thickness as a result of encrustations. The original pit membrane can be detected (arrows). 44,100X. (C) View of a segment of a scalariform perforation plate from black tupelo heartwood showing encrustations deposited on perforation plate bars. 2,300X. (D) Cross-sectional view of perforation plate bars from black tupelo heartwood. Notice the high degree of encrustations around the bars but not completely sealing the opening as in sweetgum heartwood. 7,900X. (Photos from Thomas 1976.)

Summary.—Substantial anatomical differences in these three species influence fluid penetration into them. In hickory vessels play a minor role in fluid penetration due to obstructions in their flow paths by deposition of gum and formation of tyloses. In addition, all vessels are isolated by parenchyma from direct communication with the longitudinal fiber elements, which in hickory, conduct substantial fluid flow through thin non-encrusted fiber-to-fiber pit membranes.

In sweetgum heartwood tyloses and thick and heavily encrusted interfiber pit membranes greatly reduce penetrability by blocking both perforation plates and intervessel pits.

Although black tupelo heartwood contains encrustations, they do not completely block perforation plates or pits. This and the absence of tyloses allow conduction through heartwood vessels and fluid penetration of the wood.

VARIATION AMONG SPECIES

Choong et al. (1974) measured gas (nitrogen) permeability in longitudinal, radial, and tangential directions in corewood and sapwood of 22 species of hardwoods grown on pine sites (table 3-1). Wood was sampled at 6-foot and 14-foot heights in trees averaging about 6 inches dbh. Evaluations were made at 0-percent moisture content (ovendried under vacuum) and subsequently at 20-percent moisture content. At completion of these observations, longitudinal permeability to water (deareated) was measured on saturated specimens.

In these hardwoods, radial gas permeability averaged more than twice that in the tangential direction, but permeability parallel to the grain was thousands of times greater than either. The average ratio of longitudinal to radial to tangential gas permeability in the ovendry hardwoods studied was 21,661:2.30:1 (table 8-14).

Among-species variation in longitudinal gas permeability was very large (table 8-15) as was within-species variation (fig. 8-36). Similarly, transverse permeability variation among species was substantial (table 8-16) and variation within species was great (fig. 8-37). Differences among and between species, trees, structural direction, and wood type were all statistically significant; the effect of height in stem, however, was generally negligible.

Generally the differences in longitudinal permeability between sapwood and corewood were significant, but differences in the transverse direction were not. For most species, differences between radial and tangential flow were not significant, but the average radial permeability tended to be higher than tangential permeability (table 8-14).

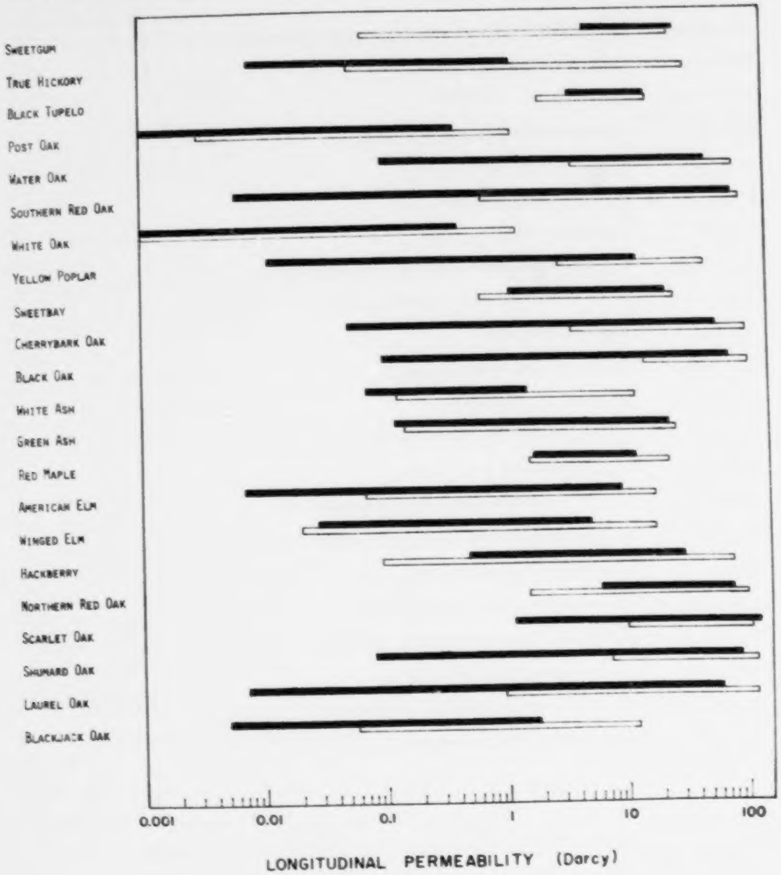

Figure 8-36.—Within-species ranges in gas permeability in the longitudinal direction for 22 hardwoods at 0-percent moisture content. Shaded bars are for corewood; unshaded bars are sapwood. (Drawing after Choong et al. 1974.)

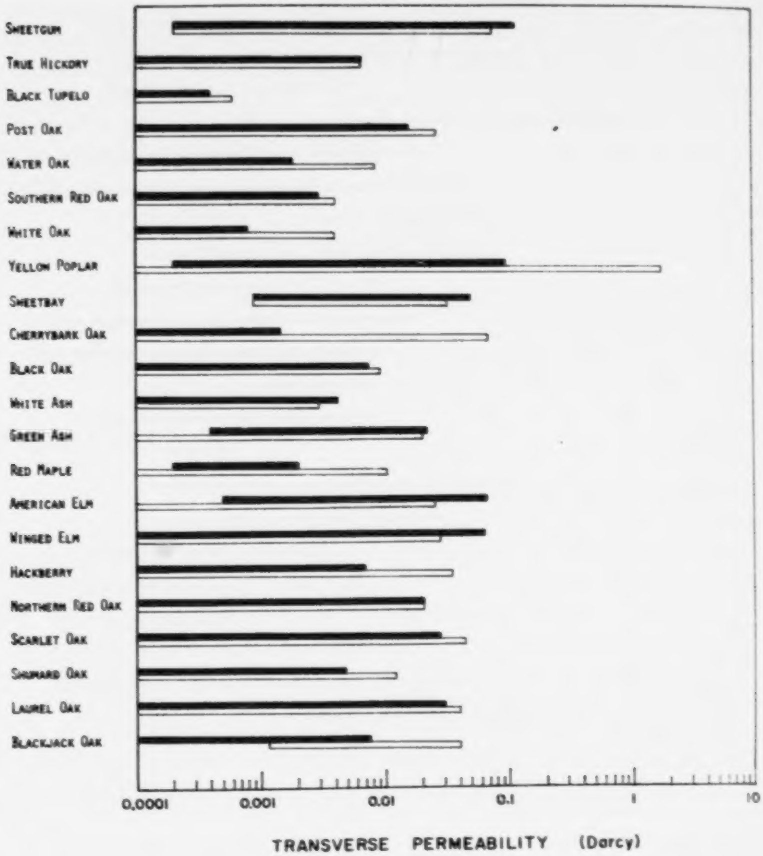

Figure 8-37.—Within-species ranges in gas permeability in the transverse directions for 22 hardwoods at 0-percent moisture content. Shaded bars are tangential movement; unshaded bars are radial movement. (Drawing after Choong et al. 1974.)

TABLE 8-14.—*Ratios of longitudinal, radial, and tangential (L/R/T) gas permeability values in 22 hardwoods at 0-percent moisture content* (Choong et al. 1974).

Species	L:R:T ratio (mean values)	Extreme range[1]
Ash, green	1,598 : 1.24 : 1	64,708 : 1
Ash, white	2,712 : .80 : 1	119,890 : 1
Elm, American	491 : .89 : 1	35,361 : 1
Elm, winged	201 : .69 : 1	180,477 : 1
Hackberry	12,871 : 2.77 : 1	758,454 : 1
Hickory	3,481 : .79 : 1	352,261 : 1
Maple, red	11,379 : 1.38 : 1	113,117 : 1
Oak, black	25,298 : 12.10 : 1	708,224 : 1
Oak, blackjack	844 : 4.25 : 1	118,299 : 1
Oak, cherrybark	143,045 : 1.33 : 1	691,618 : 1
Oak, chestnut	—	—
Oak, laurel	47,687 : 5.83 : 1	1,136,673 : 1
Oak, northern red	17,902 : 1.39 : 1	956,606 : 1
Oak, post	100 : 1.73 : 1	12,144 : 1
Oak, scarlet	8,956 : 1.82 : 1	1,247,256 : 1
Oak, Shumard	37,124 : 1.69 : 1	1,141,323 : 1
Oak, southern red	43,339 : 1.56 : 1	958,710 : 1
Oak, water	82,603 : 2.00 : 1	830,848 : 1
Oak, white	3,558 : 3.50 : 1	133,432 : 1
Sweetbay	1,585 : .67 : 1	29,203 : 1
Sweetgum	1,598 : 1.10 : 1	147,807 : 1
Tupelo, black	27,423 : 1.00 : 1	167,513 : 1
Yellow-poplar	2,753 : 2.09 : 1	230,572 : 1

[1] Ratio of highest longitudinal permeability to lowest transverse (tangential) permeability observed.

TABLE 8-15.—*Longitudinal gas (nitrogen) permeability of ovendry wood from 22 hardwoods grown on southern pine sites and ratios between longitudinal gas permeability at 0- and at 20-percent moisture content* (Choong et al. 1974[1])

Species	Sapwood	Corewood[2]	Permeability ratio (0%/20% MC)
	Darcy		
Ash, green	3.8	1.7	1.1
Ash, white	2.0	.8	1.7
Elm, American	5.8	1.3	1.3
Elm, winged	4.0	1.1	.9
Hackberry	19.3	14.1	1.3
Hickory	7.9	1.3	1.7
Maple, red	10.3	7.4	1.2
Oak, black	66.8	28.4	1.5
Oak, blackjack	2.5	.5	2.4
Oak, cherrybark	69.2	12.9	1.8
Oak, chestnut	—	—	—

See footnotes on page 628.

TABLE 8-15.—*Longitudinal gas (nitrogen) permeability of ovendry wood from 22 hardwoods grown on southern pine sites and ratios between longitudinal gas permeability at 0- and at 20-percent moisture content* (Choong et al. 1974[1])—Continued

Species	Sapwood	Corewood[2]	Permeability ratio (0%/20% MC)
	Darcy	*Darcy*	
Oak, laurel	36.3	21.1	1.5
Oak, northern red	61.9	56.7	1.4
Oak, post	.2	.1	1.4
Oak, scarlet	55.4	35.1	1.5
Oak Shumard	72.5	25.2	1.5
Oak, southern red	64.8	9.7	1.9
Oak, water	32.4	16.6	1.0
Oak, white	1.4	.0[3]	1.8
Sweetbay	15.0	11.4	1.4
Sweetgum	13.9	15.3	1.5
Tupelo, black	8.1	8.4	1.1
Yellow-poplar	29.0	1.9	1.3

[1] Each value is based on 28 to 42 observations of wood taken at 6- and 14-foot stem heights from trees averaging about 6 inches dbh.

[2] Corewood was sampled from central portions of stems adjacent to the pith, but was not necessarily heartwood.

[3] Near zero value, i.e., 0.045 Darcy.

TABLE 8-16—*Transverse gas (nitrogen) permeability of ovendry wood from 22 hardwoods grown on southern pine sites, and ratios between transverse gas permeability at 0- and at 20-percent moisture content* (Choong et al. 1974)[1]

Species	Radial movement		Tangential movement		Permeability ratio
	Sapwood	Corewood[2]	Sapwood	Corewood[2]	(0%/20% MC)
	Darcy x 1,000[3]				
Ash, green	3.4	1.7	1.9	2.4	0.44
Ash, white	.4	.4	.5	.2	.39
Elm, American	6.7	6.6	7.5	—	.67
Elm, winged	8.2	9.0	12.4	—	.57
Hackberry	4.4	2.4	1.3	1.4	.50
Hickory	1.2	.9	1.0	1.9	.44
Maple, red	1.3	.9	.8	.7	.27
Oak, black	4.4	1.6	2.1	1.6	.84
Oak, blackjack	9.3	3.3	2.0	2.2	.63
Oak, cherrybark	.5	.4	.3	.4	.30
Oak, chestnut	—	—	—	—	—
Oak, laurel	4.5	2.2	.6	.5	.55
Oak, northern red	3.5	5.1	1.3	4.5	.40
Oak, post	2.8	.6	1.1	1.5	.43
Oak, scarlet	10.6	7.4	5.6	4.4	.54
Oak, Shumard	2.2	2.1	1.4	1.2	.19

See footnotes on page 629.

TABLE 8-16—*Transverse gas (nitrogen) permeability of ovendry wood from 22 hardwoods grown on southern pine sites, and ratios between transverse gas permeability at 0- and at 20-percent moisture content* (Choong et al. 1974)[1]—Continued

Species	Radial movement		Tangential movement		Permeability ratio
	Sapwood	Corewood[2]	Sapwood	Corewood[2]	(0%/20% MC)
	Darcy x 1,000[3]				
Oak, southern red . . .	2.0	.8	1.1	.5	.26
Oak, water	.8	.6	.3	.1	.76
Oak, white	1.0	.4	.2	.2	.37
Sweetbay	5.9	5.4	10.0	5.5	.57
Sweetgum	12.5	5.6	10.4	6.5	.40
Tupelo, black	.4	.3	.3	.2	.39
Yellow-poplar	14.3	10.0	3.1	4.0	.48

[1] Each value is based on 19 to 62 observations of wood taken at 6- and 14-foot stem heights from trees averaging about 6 inches in dbh.

[2] Corewood was sampled from central portions of stems adjacent to the pith, but was not necessarily heartwood.

[3] Divide tabulated values by 1,000 to obtain Darcy units.

Moisture content of wood significantly affects longitudinal permeability. Gas permeability decreases with an increase in moisture content from 0 to 20 percent (table 8-15, 4th column). Transverse gas permeability, however, is less in these woods at 20-percent moisture content than when they are ovendry (table 8-16, 6th column).

Gas permeability of wood is closely correlated with its liquid permeability; in woods of high permeability, gas permeability is lower than liquid permeability, however (fig. 8-38). Absolute values are difficult to obtain by either system, due to turbulence in gases flowing through highly permeable wood and entrained bubbles in liquid flow.

A separate determination of longitudinal gas (air) permeability of these same 22 hardwoods from the collection described by table 3-1 was made by Siau et al. (1978). Specimens measuring 2.5 cm square by 12.8 cm long were evaluated at 6-percent moisture content by Siau's (1971, p. 43) technique. Northern red oak, yellow-poplar, and sweetbay all had air permeability values in excess of 20 Darcy, while white ash, blackjack oak, hickory, post oak, white oak, and low-permeability specimens of green ash and cherrybark oak had permeability of less than 0.3 Darcy (table 8-17). From table 8-15, the data of Choong et al. (1974) for sapwood and corewood nitrogen permeability have been averaged and listed opposite Siau's data in table 8-17. Both sets of specimens came from the same trees. Within-tree variability, as well as differing measurement techniques, probably accounts for the different permeability ranking by the two teams of investigators.

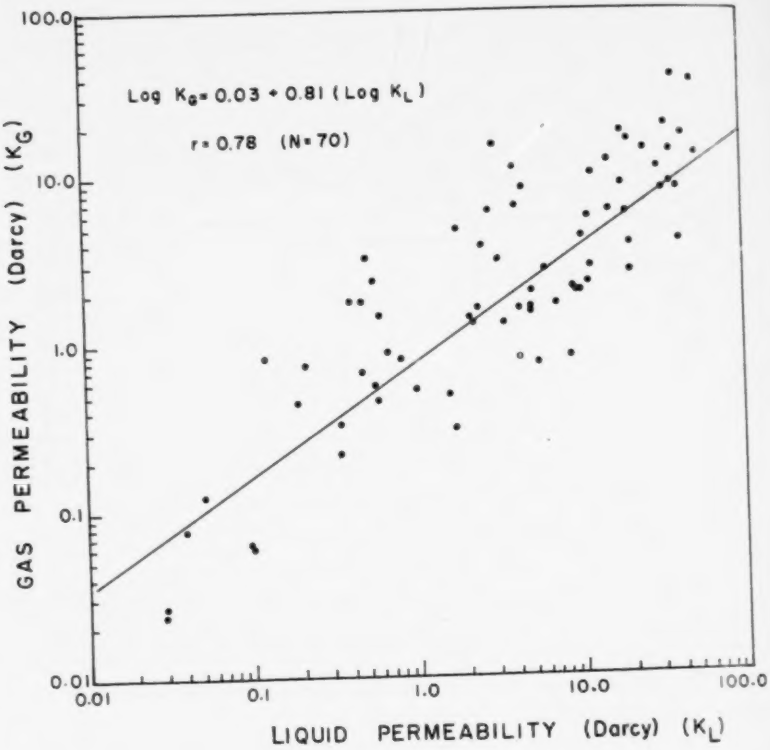

Figure 8-38.—Correlation between longitudinal gas permeability (nitrogen) at 0-percent moisture content and liquid permeability (water) in water saturated specimens of 22 hardwoods. (Drawing after Choong et al. 1974.)

TABLE 8-17.—*Longitudinal permeability to air and nitrogen of dry stemwood of 22 species of hardwoods grown on southern pine sites.*

Species	Air permeability[1]	Nitrogen permeability[2]
	Darcy	
Northern red oak	35.1	59.3
Yellow-poplar	30.4	15.5
Sweetbay	24.1	13.2
Cherrybark oak	19.3[3] .1[4]	41.1
Scarlet oak	16.8	45.2
Sweetgum	14.5	13.6
Black tupelo	13.9	8.3
Southern red oak	13.0	37.3
Shumard oak	11.7	48.8
Red maple	7.2	8.8
American elm	4.7	3.6
Water oak	4.6	24.5
Black oak	3.8	47.6
Hackberry	3.3	16.7
Winged elm	2.2	2.6
Green ash	1.9[3] .2[4]	2.7
Laurel oak	1.6	28.7
White ash	.26	1.4
Blackjack oak	.22	1.5
Hickory	.12	4.6
Post oak	.08	.1
White oak	.08	.7

[1] Data from Siau et al. (1978). Specimens (evaluated at 6-percent moisture content) were drawn from a range of radial positions in stemwood measuring about 6 inches in diameter. Because two classes of permeabilities were observed in green ash and cherrybark oak, averages for the two classes are tabulated.

[2] Data from Choong et al. (1974) are averaged from sapwood and corewood values in table 8-14; specimens were ovendry when evaluated.

[3] High-permeability specimens.

[4] Low-permeability specimens.

In the foregoing four tabulations of permeability of woods described by table 3-1, sweetgum appears to have relatively high permeability; even the corewood proved fairly permeable in both longitudinal and transverse directions. It is likely that heartwood of old-growth sweetgum from bottomland sites is significantly less permeable than the corewood of small sweetgum trees from southern pine sites.

Quantitative data on permeability of chestnut oak wood from southern pine sites is lacking, but Paul (1942) observed that second-growth chestnut oak, although a species of the white oak group, is much more porous than white oak; it is not suitable for tight cooperage unless coated ot impregnated to make it impermeable.

WITHIN-TREE VARIABILITY

In the 6-inch trees studies by Choong et al. (1974), the relationship of height in stem to longitudinal permeability was generally nonsignificant; in two of the 22 species (sweetgum and white ash) stemwood permeability was slightly greater at the 6-foot level than at 14 feet above ground.

In most of the species (table 8-14 and 8-15), sapwood has higher longitudinal permeability than corewood. This is true even in some species in which heartwood is not readily distinguished from sapwood by color differences. In four species, sweetgum, black tupelo, hackberry, and northern red oak, there was no difference in permeability between corewood and sapwood. In northern red oak, although heartwood was well developed, corewood permeability was not different from that of the sapwood and was higher than corewood permeability of the other eight red oaks. This may indicate that heartwood vessels of northern red oak contain fewer tyloses than do the other red oaks tested.

In analyses of transverse permeability in these small trees, only among-tree variations within a species were generally significant. Height in stem, wood type, and structural direction in most cases had no significant relationship to permeability.

Limited data on within-tree variation in larger specimens of four species (sweetgum, northern red oak, white oak, and yellow-poplar have been published).

Sweetgum.—Choong and Fogg (1971) analyzed gas permeability (nitrogen) at 7-foot-height intervals in stemwood of a 20-inch sweetgum tree harvested near Baton Rouge, Louisiana; lower sections of the tree were slightly more permeable than upper sections, as follows:

Height	Permeability	
	Longitudinal	Transverse
Feet	*Darcy*	
7	1.37	0.016
14	1.11	.018
21	1.02	.014
28	1.31	.007
35	.40	.011
42	.23	—

Heartwood was significantly less permeable than sapwood as follows:

Tissue and fractional distance from pith to bark	Permeability	
	Longitudinal	Transverse
	Darcy	
Heartwood		
1/5	0.26	0.008
Sapwood		
2/5	1.69	.012
3/5	1.29	.123
4/5	1.05	.183

Northern red oak.—Longitudinal permeability to water in green northern red oak at breast height was found by Chen (1975) to be greatest in sapwood nearest the bark, and least in heartwood (fig. 8-39).

White oak.—Green white oak appears to be impermeable to water at all breast-height radial positions in the stem (fig. 8-39).

Yellow-poplar.—At breast height, heartwood of green yellow-poplar is nearly impermeable to water, but sapwood has a pattern of radial variation like that of northern red oak (fig. 8-39) (Chen 1975).

Choong and Fogg (1972) measured longitudinal gas permeability (nitrogen) in stemwood of a 15-inch 40-year-old yellow-poplar held at 18-percent moisture content and observed a pattern of variation similar to that found by Chen (1975). Also, Choong and Fogg noted that inner heartwood diminished linearly in longitudinal permeability from about 0.7 Darcy at 1-foot height to about 0.2 Darcy at the 31-foot level. Middle sapwood longitudinal permeability was minimum at the 1- and 31-foot levels (about 2.5 Darcy); at intermediate heights in the stem, permeability in middle sapwood was fairly uniform at about 3.5 Darcy.

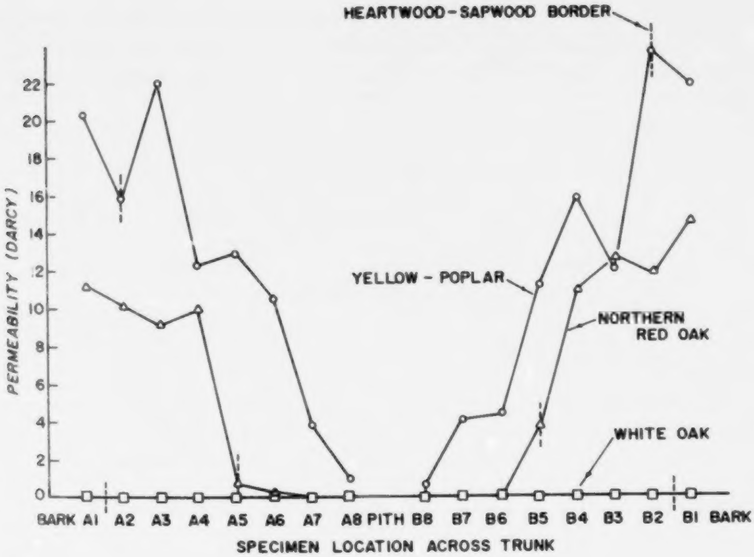

Figure 8-39.—Radial variation, across a stem diameter-line at breast height, in longitudinal permeability to water in green wood of three hardwood trees. Trees measured about 15 inches in diameter. (Drawing after Chen 1975.)

EFFECT OF TREATMENTS

The permeability of wood is affected by its drying history. Chen (1974) found that air drying distorted, but did not break, the scalariform plates in vessel segments of yellow-poplar. Subsequent work by Chen (1975) showed that air drying significantly increased radial and longitudinal permeability of three hardwoods, as follows (to convert millidarcy units to Darcy units, divide by 1,000):

Statistic	Yellow-poplar sapwood	Northern red oak heartwood	White oak heartwood
Longitudinal permeability			
Green (Darcy)	12.131	18.700	0.00269
Airdried (Darcy)	15.926	20.310	.00272
Increase in dried wood (percent)	31	9	Not significant
Radial permeability			
Green (millidarcy)	0.406	0.052	0.022
Airdried (millidarcy)	1.173	.081	.040
Increase in dried wood (percent)	189	55	82

Treatments other than drying also affect permeability. Nicholas (n.d.) has reviewed some possibilities, all of which contemplate either dissolving extraneous material that blocks flow, or modifying anatomical structures—particularly pit membranes—that block flow of fluids. A partial listing of such treatments follows:

Treatment	Comment
Pre-extraction with a solvent	Recovery of such solvents is expensive
Steaming	Drying rates of oaks (a measure of permeability) can be increased significantly by pre-steaming; drying rate of sweetgum is unaffected (Simpson 1975)
Chemical degradation of pit membranes	Sodium chlorite, pulping liquors, acids and bases have been used to increase permeability, but strength loss results from such treatments. Hot ammonium oxalate has also been used to increase permeability
Fungal attack	Fungal hyphae penetrate sapwood pit membranes; such treatment has not proven effective on heartwood
Bacterial attack	The bacteria excrete an enzyme that attacks pit membranes of sapwood; such treatment has not been effective on heartwood
Treatment with isolated enzymes	Sapwood pit membranes are rendered more permeable, but not those of heartwood

TREATABILITY AND RETENTION

Although permeability is correlated to treatability of woods, as measured by penetration and retention of treating fluid, the correlation inexact. For a discussion of these aspects of treating hardwoods, see chapter 21.

8-7 MECHANISMS OF DRYING

For a discussion of the mechanism of drying, readers are referred to Hart (1965) or to a summary of his work found in Agriculture Handbook 420 (Koch 1972 pp. 317-328). Those interested in mathematical models of diffusion in wood will find the following references useful:

Citation	Subject
Bramhall 1976, 1977, 1978, 1979abc	Fick's laws, diffusion, and mathematical models
Choong and Fogg 1968	Moisture movement in six wood species
Choong and Skaar 1972	Diffusivity and surface emissivity in wood drying
Kelly and Hart 1970	Water sorption rates by wood cell walls
Martin and Moschler 1970	Measurement of diffusion coefficients in wood by the Matano solution
McNamara and Hart 1971	An analysis of interval and average diffusion coefficients for unsteady-state movement of moisture in wood
Moschler and Martin 1968	Diffusion equations in experimental wood drying
Rosen 1976	Exponential dependency of the moisture diffusion coefficient on moisture content
Rosen and Bramhall 1976	Diffusion theories and pair matching of samples
Siau 1971	Flow in wood
Simpson 1973b	Relation of comparative diffusion rates of oak rays and surrounding tissue to check formation
Simpson 1974	Measuring dependence of diffusion coefficient of wood on moisture concentration by absorption exeriments.
Skaar 1972	Water in wood

Techniques and procedures for drying hardwoods are discussed in chapter 20.

8-8 LITERATURE CITED

Akins, V., and M. Y. Pillow. 1950. Occurrence of gelatinous fibers and their effect upon properties of hardwood species. Proc. For. Prod. Res. Soc. 4:254-264.

American Society for Testing Materials. 1974. Standard methods of test for moisture content of wood. ASTM Designation D 2016-74, pp. 580-595. Philadelphia, Pa.: Am. Soc. for Testing and Mater.

Anderson, A. B. 1961. The influence of extractives on tree properties. I. California redwood (*Sequoia sempervirens*). J. Inst. Wood. Sci. 8:14-34.

Banks, W. B. 1973. Water uptake by scots pine sapwood, and its restriction by the use of water repellents. Wood Sci. & Technol. 7:271-284.

Barkas, W. W. 1949. The swelling of wood under stress. 103 p. London: His Majesty's Stationery Off.

Barkas, W. W., R. F. S. Hearmon, and H. F. Range. 1953. Mechanical properties of wood and paper. R. Meredith, ed. 298 p. New York, N. Y.: Interscience Publ., Inc.

Barrie, J. A. 1968. Water in polymers. *In* Diffusion in polymers. J. Crank and G. S. Park, eds. New York, N. Y.: Academic Press Inc.

Beall, F. C., P. R. Blankenhorn, and G. R. Moore. 1974. Carbonized wood—physical properties and use as an SEM preparation. Wood Sci. 6:212-219.

Bello, E. D. 1968. Effect of transverse compressive stress on equilibrium moisture content of wood. For. Prod. J. 18(2):69-76.

Bersenev, A. P., B. V. Vasil'ev, and V. H. Onucin. 1963. (Determination of wood moisture content by the method of nuclear magnetic resonance.) Les. Zh. 6(1):127-130.

Beutler, A. J. 1965. An infrared backscatter moisture gage. Tappi 48-490-493.

Bosshard, H. H. 1956. Uber die aniosotropie der Holzschwindung. Holz als Roh- und Werkstoff 14:285-295.

Bower, R. K., and J. D. Wellons. 1974. Sorption of styrene and acrylonitrile by wood aerogels. Wood Sci. 7:123-129.

Boyd, J. D. 1977. Relationship between fibre morphology and shrinkage of wood. Wood Sci. and Technol. 11:3-22.

Bramhall, G. 1976. Semi-empirical method to calculate kiln-schedule modifications for some lumber species. Wood Sci. 8:213-222.

Bramhall, G. 1977. More on application of Fick's laws. Wood Sci. 9(4):149-153.

Bramhall, G. 1978. Sorption diffusion in the drying of solids. Fibre Sci. and Technol.

Bramhall, G. 1979a. Mathematical model for lumber drying. I. Principles involved. Wood Sci. 12:14-21.

Bramhall, G. 1979b. Mathematical model for lumber drying. II. The model. Wood Sci. 12:22-31.

Bramhall, G. 1979c. Sorption diffusion in wood. Wood Sci. 12(1):3-13.

Bristow, J. A., and E. L. Back. 1969. The moisture content of fibre building boards Svensk Papperstidn. 72(11):367-374.

Browning, B. L. 1967. Methods of wood chemistry. Vol. I, 384 p. N. Y.: Interscience Pub.

Burmeister, A., and W. E. Wille. 1976. (Reduction in swelling of wood in different ranges of air humidity. II. Changes in cell-wall structure caused by heat treatment.) Holz als Roh- und Werkstoff 34:87-90.

Busker, L. H. 1968. Measurement of water content above 30% by microwave absorption methods. Tappi 51:348-353.

Campbell, W. B. 1933. The cellulose-water relationship in papermaking. Can. Dep. Interior For. Serv. Bull. 84, 52 p.

Campbell, R. N. 1959. Fungus sap-stains of hardwoods. South. Lumberman 199(2489): 115-120.

Cassens, D. L., and E. T. Choong. 1975. Fuel values and volumes for selected delta hardwood barks. South. Lumberman 231(2862): 13-14.

Chech, M. Y. 1968. Effect of alcohol in preventing collapse under extreme drying conditions. For. Prod. J. 18(6):35-42.

Chen, P. Y. S. 1973. Investigation of pressure-solvent-displacement of moisture in wood. Wood Sci. 6:61-64.

Chen, P. Y. S. 1974. A note on the effect of air-drying on vessel openings and air-blockage in yellow-poplar. Wood and Fiber 5:308-311.

Chen, P. Y. S. 1975. Effect of air-drying and rewetting on hardwood permeability. Wood Sci. 7:280-283.

Choong, E. T. 1969a. Effect of extractives on shrinkage and other hygroscopic properties of ten southern pine woods. Wood and Fiber 1:124-133.

Choong, E. T. 1969b. Moisture and the wood of the southern pines. For. Prod. J. 19(2):30-36.

Choong, E. T., and D. L. Cassens. 1976. Physical chartacteristics of bark of several delta hardwoods. LSU Wood Util. Notes No. 28, 4 p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A & M Coll., Baton Rouge, La.

Choong, E. T., and P. J. Fogg. 1968. Moisture movement in six wood species. For. Prod. J. 18(5):66-70.

Choong, E. T., and P. J. Fogg. 1971. Permeability variation within a sweetgum tree. LSU Wood Util Notes No. 22, 4 p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A & M Coll., Baton Rouge, La.

Choong, E. T., and P. J. Fogg. 1972. Variation in permeability and treatability in shortleaf pine and yellow-poplar. Wood and Fiber 4:2-12.

Choong, E. T., and F. G. Manwiller. 1976. Dimensional and relative hygroscopic properties of hardwoods from southern pine sites. Wood Sci. 9:39-43.

Choong, E. T., and C. Skaar. 1972. Diffusivity and surface emissivity in wood drying. Wood and Fiber 4:80-86.

Choong, E. T., and F. O. Tesoro, and F. G. Manwiller. 1974. Permeability of twenty-two small diameter hardwoods growing on southern pine sites. Wood and Fiber 6:91-101.

Chow, P. 1976. Effects of moisture on the hardness of selected commercial wood-base panel materials. For. Prod. J. 26(7):41-44.

Clark, A., III. 1975. Seasonal variation in weight of young copice sycamore. Wood Sci. 7:261-266.

Clark, A. III, and J. G. Schroeder. 1977. Biomass of yellow-poplar in natural stands in western North Carolina. U.S. Dep. Agric. For. Serv. Res. Pap. SE-165. 41 p.

Clark, A. III, D. R. Phillips, and H. C. Hitchcock III. 1980a. Predicted weights and volumes of southern red oak trees on the Highland Rim in Tennessee. Res. Pap. SE-208, U.S. Dep. Agric. For. Serv. 23 p.

Clark, A. III, D. R. Phillips, and H. C. Hitchcock III. 1980b. Predicted weights and volumes of scarlet oak trees on the Tennessee Cumberland Plateau. Res. Pap. SE-214, U.S. Dep. Agric., For. Serv. 23 p.

Clark, A. III, D. R. Phillips, and J. G. Schroeder. 1980c. Predicted weights and volumes of northern red oak trees in western North Carolina. Res. Pap. SE-209, U.S. Dep. Agric., For. Serv. 22 p.

Duff, J. E. 1966. A probe for accurate determination of moisture content of wood products in use. U.S. Dep. Agric. For. Serv., Res. Note FPL-0142. 10 p.

Ellwood, E. L., and B. A. Ecklund. 1963a. The effect of organic liquids on collapse and shrinkage of wood. I. Effect of degrees of replacement. For. Prod. J. 13:291-298.

Ellwood, E. L., and B. A. Ecklund. 1963b. The effect of organic liquids on collapse and shrinkage of wood. II. Effect of degrees of replacement. For. Prod. J. 13:350-354.

Ellwood, E. L., B. A. Ecklund, and E. Zavarin. 1963. The effect of organic liquids on collapse and shrinkage of wood. III. Chemical influences. For. Prod. J. 13:401-404.

Ellwood, E. L., R. C. Gilmore, and A. J. Stamm. 1972. Dimensional stabilization of wood with vinyl monomers. Wood Sci. 4:137-141.

Erickson, H. D. 1949. Relation of specific gravity to shrinkage and of these factors to growth in yellow-poplar. J. Agric. Res. 78(5, 6): 103-127.

Feist, W. C., and H. Tarkow. 1967. Polymer exclusion in wood substance: a new procedure for measuring fiber saturation points. For. Prod. J. 17(10):65-68.

Furuno, T., and T. Gotto. 1974. Structure of the interface between wood and synthetic polymer. V. The penetration of polyethylene glycol into woody cell wall. J. of the Japan Wood Res. Soc. 20(9):446-452.

Gerry, E. 1914. Tyloses: their occurrence and practical significance in some American woods. J. Agric. Res. 1:445-470.

Gibson, E. J. and D. Rusten. 1964. Determination of the moisture content of pulp chips by an instrument method. Norsk Skogindustri 18:351-356.

Hailwood, A. J., and S. Horrobin. 1946. Absorption of water by polymers: analysis in terms of a simple model. Trans. Faraday Soc. 42B:84-102.

Hallock, H., and E. Bulgrin. 1972. Stabilization of hard maple flooring with polyethylene glycol 1000. U.S. Dep. Agric. For. Serv., Res. Pap. FPL. 187. 8 p.

Hann, R. A. 1969. Longitudinal shrinkage in seven species of wood. U.S. Dep. Agric. For. Serv., Res. Note FPL-0203. 13 p.

Hann, R. A., A. E. Oviatt, D. M. Markstrom, and J. E. Duff. 1970. Moisture content of laminated timbers. U.S. Dep. Agric. For. Serv., Res. Pap., FPL 149. 6 p.

Hart, C. A. 1965. The drying of wood. N. C. State Univ. Sch. For. Tech. Rep. 27, 24 p.

Hart, C. A. 1970. Water-filled lumens in steady-state flow in oak and poplar. Wood and Fiber 1:308-318.

Hart, C. A., P. J. Przestrzelski, and F. J. Wheeler. 1974. Entrapped lumen water in hickory during desorption. Wood Sci. 6:356-362.

Hart, C. A., and W. M. Darwin, Jr. 1971. The slow drying rate of white oak. Wood Sci. 4:46-54.

Hedlin, C. P. 1967. Sorption isotherms of twelve woods at subfreezing temperatures. For. Prod. J. 17(12):43-48.

Heebink, B. G. 1966. Some thoughts on the term "EMC. " Soc. Wood. Sci. and Technol. Log. November, pp. 1-3.

Hejjas, J., and M. Salamon. 1977. Measurement of lumber moisture content—A critique. Wood Sci. 10:56-61.

Henderson, L. G., and E. T. Choong. 1968. Variation in moisture content of standing sweetgum trees in Louisiana. LSU For. Notes No. 81, 3 p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A & M Coll., Baton Rouge, La.

Higgins, N. C. 1957. The equilibrium moisture content—relative humidity relationship of selected native and foreign woods. For. Prod. J. 7:371-377.

Hill, J. L., and R. H. Munkittrick. 1970. Performance of remote moisture sensing devices. For. Prod. J. 20(8):39-46.

Hitchcock, H. C. III. 1978. Aboveground tree weight equations for hardwood seedlings and saplings. Tappi 61(10):119-120.

Hoadly, R. B. 1969. Perpendicular-to-grain compression set induced by restrained swelling. Wood Sci. 1:159-166.

Hopkins, W. C. 1960. Moisture content of building structural members. For. Prod. J. 10:506-508.

James, W. L. 1963. Electric moisture meters for wood. U.S. Dep. Agric. For. Serv., Res. Note FPL-08. 24 p.

James, W. L. 1965. Effects of wood preservatives on electrical moisture-meter readings. U.S. Dep. Agric. For. Serv., Res. Note FPL-0106. 12 p.

James, W. L. 1968.,Effect of temperature on readings of electric moisture meters. For. Prod. J. 18(10):23-31.

James, W. L. 1975a. Electric moisture meters for wood. FPRS News-Digest B-4. 7, 4 p. For. Prod. Res. Soc., Madison, Wis.

James, W. L. 1975b. Electric moisture meters for wood. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. FPL-6. 27 p.

Jett, J. B., and B. J. Zobel. 1975. Wood and pulping properties of young hardwoods. Tappi 58(1):92-96.

Kajanne, P., and A. Hollming. 1958. On moisture determination in wood chips using gamma ray scattering. Paperi ja Puu 40(4a):153-157.

Kajita, H. 1975. The bark-water relationship. J. of the Soc. of Mater. Sci. Jap. 24(264):862-866.

Kajita, H. 1976. (The heat of wetting of wood in water (1).) Bull. of the Kyoto Prefect. Univ. For. 20:49-61.

Kajita, H., M. Yoneda, T. Koshijima, J. Mukudai, and S. Yata. 1977. Heat of wetting of wood in water. (2) Heat of wetting of the constituents of wood in water. Matl. Sci. (Kyoto) 26(284):417-423.

Kass, A. J. 1965. Shrinkage stress in externally restrained wood. For. Prod. J. 15(6):225-232.

Kauman, W. G. 1956. Equilibrium moisture content relations and drying control in superheated steam drying. For. Prod. J. 6:328-332.

Kellison, R. C., and B. J. Zobel. 1971. Wood specific gravity and moisture content of five hardwood species of the southern United States. J. Ser. Pap. No. 3408, 13 p. Agric. Exp. Stn., N. C. State Univ., Raleigh.

Kellogg, R. M., and F. F. Wangaard. 1969. Variation in the cell-wall density of wood. Wood and Fiber 1:180-204.

Kelly, M. W., and C. A. Hart. 1970. Water vapor sorption rates by wood cell walls. Wood and Fiber 1:270-282.

Kent, A. C., H. N. Rosen, and B. M. Hart. 1981. Determination of equilibrium moisture content of yellow-poplar sapwood above 100°C with the aid of an experimental psychrometer. Wood Sci. Technol. 15:93-103.

King, G. 1960. Theories of multi-layer adsorptin. *In* Moisture in textiles, pp. 69-82. J. S. W. Hearle and R. H. Peters, eds. New York, N. Y.: Textile Book Publ. Inst., Inc.

Koch, P. 1972. Utilization of the southern pines. U.S. Dep. Agric. For. Serv., Agric. Handb. 420. 1663 p. 2 vol. U.S. Govt. Print. Off., Washington, D. C.

Koehler, A. 1931. Longitudinal shrinkage of wood. Am. Soc. Mech. Eng. Trans. 53(5):17-20.

Kollmann, F. F. P., and W. A. Côté, Jr. 1968. Principles of wood science and technology. I. Solid wood. 592 p. N. Y.: Springer-Verlag, New York Inc.

Kollmann, F., and A. Schneider. 1963. Uber das sorptionsverhalten warmebehandelter Holzer. Holz als Roh- und Werkstoff 21:77-85.

Kruse, K. 1954. Moisture changes with different relative humidity conditions in plant humidification equipment. J. of the For. Prod. Res. Soc. 4:148.

Kubinsky, E. 1971. Influence of steaming on the properties of *Quercus rubra* L. wood. Holzforschung 25:78-83.

Kubinsky, E., and G. Ifju. 1974. Influence of steaming on the properties of red oak. Part II. Changes in shrinkage and related properties. Wood Sci. 7:103-110.

Kubler, H. 1962. Shrinkage and swelling of wood by coldness. Holz als Roh- und Werkstoff 20:364-368.

Kubler, H. 1970. A note on recovery of excessive shrinkage in wood. Wood Sci. 3:62-64.

Ladell, J. L. 1957. High-temperature kiln-drying of eastern Canadian softwoods, drying guide and tentative schedules. For. Prod. Lab. of Can. FPL Tech. Note 2, 18 p. Ottawa.

Lassen, L. E., and G. A. Cooper. 1960. Significance of tension wood in furniture cuttings of red oak. U.S. Dep. Agric. For. Serv., FPL No. 2193, 12 p.

Libby, T. B. and J. G. Haygreen. 1967. Moisture content change induced by tensile stress in whole wood. J. Inst. Wood Sci. 3(18):54-60.

Loos, W. E. 1961. The relationship between gamma ray absorption and wood moisture content and density. For. Prod. J. 11:145-149.

Loos, W. E. 1965. A review of methods for determining moisture content and density of wood by nuclear radiation techniques. For. Prod. J. 15:102-106.

Loos, W. E., and G. L. Robinson. 1968. Techniques for determining moisture in wood-plastic combinations. For. Prod. J. 18(11):36-41.

Lowery, D. P., and E. S. Kotok. 1967. Evaluation of a microwave wood moisture meter. For. Prod. J. 17(10):47-51.

Lundrstrom, J. W. 1970. On-line chip moisture measurements. Tappi 53:857-861.

Mackay, J. F. G. 1976. Effect of moisture gradients on the accuracy of power-loss moisture meters. For. Prod. J. 26(3):49-52.

Manwiller, F. G. 1975. Wood and bark moisture contents of small-diameter hardwoods growing on southern pine sites. Wood Sci. 8:384-388.

Martin, R. E., and W. W. Moschler, Jr. 1970. Measurement of diffusion coefficients in wood by the Matano solution. Wood Sci. 2:186-192.

McGinnes, E. A., Jr., S. A. Kandeel, and P. S. Szopa. 1971. Some structural changes observed in the transformation of wood into charcoal. Wood and Fiber 3:77-83.

McIntosh, D. C. 1954. Some aspects of the influence of rays on the shrinkage of wood. J. of the For. Prod. Res. Soc. 4:39-42.

McIntosh, D. C. 1955. Shrinkage of red oak and beech. For. Prod. J. 5:355-359.

McIntosh, D. C. 1957. Transverse shrinkage of red oak and beech. For. Prod. J. 7:114-120.

McLaren, A. D., and J. W. Rowen. 1951. Sorption of water vapor by proteins and polymers: a review. J. Polym. Sci. 7:289-324.

McMillen, J. M. 1955. Drying stresses in red oak: effect of temperature. For. Prod. J. 5:230-241.

McNamara, W. S., and C. A. Hart. 1971. An analysis of interval and average diffusion coefficients for unsteady-state movement of moisture in wood. Wood Sci. 4:37-45.

McNatt, J. D. 1974a. Effects of equilibrium moisture content changes on hardboard properties. For. Prod. J. 24(2): 29-35.

McNatt, J. D. 1974b. Properties of particleboards at various humidity conditions. U.S. Dep. Agric. For. Serv., Res. Pap. FPL 225. 23 p.

Merz, R. W., and G. A. Cooper. 1968. Effect of polyethylene glycol on stabilization of black oak blocks. For. Prod. J. 18(3):55-59.

Morschauser, C. R. 1954. The effect of rays on the differential shrinkage of red oak. J. For. Prod. Res. Soc. 4:280-282.

Morton, W. E., and J. W. S. Hearle. 1975. Physical properties of textile fibres. 2nd ed. 660 p. N. Y., N. Y.: John Wiley & Sons.

Moschler, W. W., Jr., and R. E. Martin. 1968. Diffusion equation solutions in experimental wood drying. Wood Sci. 1:47-57.

Nanassy, A. J. 1973. Use of wide line NMR for measurement of moisture content in wood. Wood Sci. 5:187-193.

Nanassy, A. J. 1974. Water sorption in green and remoistened wood studied by the broad-line component of the wide-line NMR spectra. Wood Sci. 7:61-68.

Nanassy, A. J. 1976. True dry-mass and moisture content of wood by NMR. Wood Sci. 9:104-109.

Nearn, W. T. 1955. Effect of water soluble extractives on the volumetric shrinkage and equilibrium moisture content of eleven tropical and domestic woods. Penn. Agric. Exp. Stn. Bull. 598, 38p.

Nicholas, D. D. (n. d.) Chemical methods of improving the permeability of wood. Wood Technol.: Chem. Aspects, pp. 33-47.

Okoh, I. K. A. 1976. Moisture sorption and electrical resistivity of some woods and barks. Ph.D. thesis. State Univ. of N. Y. Coll. of Environ. Sci. and For., Syracuse, N. Y. 183 p.

Okoh, K. I. A., and C. Skaar. 1980. Moisture sorption isotherms of the wood and inner bark of ten southern U.S. Hardwoods. Wood and Fiber 12:98-111.

Paul, B. H. 1939. Shrinkage of white oak as affected by position in the tree. J. For. 37:572-573.

Paul, B. H. 1942. Variation in the porosity of twelve species of oak. South. Lumberman 164(2063): 31-33.

Paul, B. H. 1969. Second-growth oak. Part I. The South. Lumber J. 63(1):14-15, 26, 30. Part II. Second-growth oak. The South. Lumber J. 63(1)16-18.

Paul, B. H., and R. O. Marts. 1934. Growth, specific gravity, and shrinkage of twelve delta hardwoods. J. For. 32:861-873.

Peck, E. C. 1947. Shrinkage of wood. U.S. Dep. Agric. For. Serv., Rep. R1650. 6 p. For. Prod. Lab., Madison, Wis.

Perem, E. 1964. Tension wood in Canadian hardwoods. Can. Dep. of For. Publ. No. 1057, 37 p. Ottawa, Can.: Queen's Print. and Controller of Stationery.

Phillips, D. R. 1977. Total-tree weights and volumes for understory hardwoods. Tappi 60(6):68-71.

Phillips, D. R., and J. G. Schroeder 1973. Some physical properties of yellow-poplar wood and bark. Part I—seasonal moisture content. Wood Sci. 5:265-269.

Pierce, F. T. 1929. A two-phase theory of the absorption of water vapor by cotton cellulose. J. Text. Inst. 20:T133-T150.

Preikschat, F. K., E. Preikschat, and D. F. Pope. 1974. Factors affecting automatic wood chip moisture measurement. Pap. Trade J. 158(30):21-25.

Princes Risborough Laboratory. 1975. Factors affecting fibre building boards in service. BRE Inf., March 1975, 4 p. Engl.: Princess Risborough Lab.

Rosen, H. N. 1974. Distribution of water in hardwoods: a mathematical model. Wood Sci. and Technol. 8:283-299.

Rosen, H. N. 1975. High pressure penetration of dry hardwoods. Wood Sci. 8:355-363.

Rosen, H. N. 1976. Exponential dependency of the moisture diffusion coefficient on moisture content. Wood Sci. 9:174-179.

Rosen, H. N. 1978. Interaction of alcohols and organic acids with wood. Wood Sci. 10: 151-157.

Rosen, H. N., 1980. Psychometric relationships and equilibrium moisture content of wood at temperatures above 212°F. Wood and Fiber 12(3):153-171.

Rosen, H. N., and G. Bramhall. 1976. Diffusion theories and pair matching of samples. Wood Sci. 9:1-6.

Rosen, H. N., and C. H. vanEtten. 1974. Fiber saturation point determination of once-dried wood in solvents. Wood Sci. 7:149-152.

Rosen, H. N., W. T. Simpson, and E. M. Wengert, Co-Chairman. 1969. Wood moisture content—temperature and humidity relationships. Proceedings of a Symposium. Virginia Polytechnic Institute, Blacksburg, Va., Oct. 29. 101p.

Rowell, R. M. 1977. Effects of drying method and penetration of chemicals on chemically modified southern pine. Wood Sci. 9:144-148.

Rowell, R. M., and D. I. Gutzmer. 1975. Chemical modification of wood: reactions of alkylene oxides with southern yellow pine. Wood Sci. 7:240-246.

Rowell, R. M., D. I. Gutzmer, I. B. Sachs, and R. E. Kinney. 1976. Effects of alkylene oxide treatments on dimensional stability of wood. Wood Sci. 9:51-54.

Sachs, I. B., J. C. Ward, and R. E. Kinney. 1974. Scanning electron microscopy of bacterial wetwood and normal heartwood in poplar trees. *In* Scanning electron microscopy/1974. Part II, proc. of the workshop on scanning electron microscopy and the plant sciences, pp. 453-460. Chicago, Ill.: IIT Res. Inst.

Schmidt, R. N. 1967. Some wood-moisture relations at −20°C. M.F. Thesis. Univ. Washington, Seattle. 81 p.

Schniewind, A. P. 1959. Transverse anisotropy of wood: a function of gross anatomic structure. For. Prod. J. 9:350-359.

Schniewind, A. P., and P. C. Kersavage. 1962. Influence of rate of drying and rewetting on the dimensional changes of California black oak. For. Prod. J. 12:29-33.

Schroeder, H. A. 1972. Shrinking and swelling differences betweeen hardwoods and softwoods. Wood and Fiber 4:20-25.

Schroeder, J. G., and D. R. Phillips. 1973. Some physical properties of yellow-poplar wood and bark. Part II: variations with height in the tree. Wood Sci. 6:123-126.

Schumann, D. R., and M. Y. Pillow. 1969. Effect of tension wood on hard maple used for manufactured parts. U.S. Dep. Agric. For. Serv., Res. Pap. FPL 108. 8 p.

Seborg, C. O., F. A. Simmonds, and P. K. Baird. 1938. Sorption of water vapor by papermaking materials. Irreversible loss of hygroscopicity due to drying. Pap. Trade J. 107(19):45-50.

Siau, J. F. 1969. The swelling of basswood by vinyl monomers. Wood Sci. 1:250-253.

Siau, J. F. 1971. Flow in wood. 131 p. New York, N. Y.: Syracuse Univ. Press.

Siau, J. F., and J. A. Meyer. 1966. Comparison of the properties of heat and radiation cured wood-polymer combinations. For. Prod. J. 16:47-56.

Siau, J. F., W. B. Smith and J. A. Meyer. 1978. Wood-polymer composites from southern hardwoods. Wood Sci. 10:158-161.

Simpson, W. T. 1971a. Equilibrium moisture content prediction for wood. For. Prod. J. 21(5):48, 49.

Simpson, W. T. 1971b. Moisture changes induced in red oak by transverse stress. Wood and Fiber 3:13-21.

Simpson, W. T. 1973a. Predicting equilibrium moisture content of wood by mathematical models. Wood and Fiber 5:41-49.

Simpson, W. T. 1973b. Relation of comparative diffusion rates of oak ray and surrounding tissue to check formation. Wood and Fiber 5:34-40.

Simpson, W. T. 1974. Measuring dependence of diffusion coefficient of wood on moisture concentration by absorption experiments. Wood and Fiber 5:299-307.

Simpson, W. T. 1975. Effect of steaming on the drying rate of several species of wood. Wood Sci. 7:247-255.

Simpson, W. T. 1982. Importance of relative humidity and temperature control in conditioning wood products. Wood and Fiber 14:94-103.

Simpson, W. T., and H. N. Rosen 1981. Equilibrium moisture content of wood at high temperatures. Wood and Fiber 132:150-158.

Simpson, W. T., and C. Skaar. 1968a. Effect of restrained swelling on wood moisture content. U.S. Dep. Agric. For. Serv., Res. Note FPL-0196. 4 p.

Simpson, W. T., and C. Skaar. 1968b. Effect of transverse compressive stress on loss of wood moisture. U.S. Dep. Agric. For. Serv., Res. Note FPL-0197. 3 p.

Skaar, C. 1964. Some factors involved in the electrical determination of moisture gradients in wood. For. Prod. J. 14:239-243.

Skaar, C. 1972. Water in wood. Syracuse Wood Sci. Ser. 4, 218 p. Syracuse, N. Y.: Syracuse Univ. Press.

Smith, W. R., and N. B. Gobel. 1952. The moisture content of green hickory. J. of For. 50(8):616-618.

Spalt, H. A. 1958. The fundamentals of water vapor sorption by wood. For. Prod. J. 8:288-295.

Stamm, A. J. 1935. Shrinkage and swelling of wood. Ind. Eng. Chem. 27:401-406.

Stamm, A. J. 1956. Thermal degradation of wood and cellulose. Ind. Eng. Chem. 48:413-417.

Stamm, A. J. 1964. Wood and cellulose science. 549 p. N. Y.: Ronald Press Co.

Stamm, A. J. 1971. Review of nine methods for determining the fiber saturation points of wood and wood products. Wood Sci. 4:114-128.

Stamm, A. J. 1974. Dimensional stabilization of wood with water soluble fire retardant bulking chemicals compared with polyethylene glycol-1000. Wood Sci. and Technol. 8:300-306.

Stamm, A. J., H. K. Burr, and A. A. Kline. 1946. Staybwood—heat-stabilized wood. Ind. Eng. Chem. 38:630-634.

Stamm, A. J., and W. K. Loughborough. 1935. Thermodynamics of the swelling of wood. J. Phys. Chem. 39:121-132.

Stevens, W. C. 1963 The transverse shrinkage of wood. For. Prod. J. 13:386-389.

Suchsland, O., and G. E. Woodson. 1976. Properties of medium-density fiberboard produced in an oil-heated laboratory press. U.S. Dep. Agric. For. Serv., Res. Pap. SO-116. 10 p.

Swanson, T., Stejskal, E. O. and Tarkow, H. 1962. Nuclear magnetic resonance studies on several cellulose-water systems. Tappi 45:929-932.

Taras, M. A. 1967. Moisture content variation of finished and partially finished wood homes in the Southeast. For. Prod. J. 17(8):60-63.

Teesdale, C. H., and J. D. MacLean. 1918. Relative resistance of various hardwoods to injection with creosote. U.S. Dep. Agric. Bull No. 606. 36 p.

Thomas, R. J. 1976. Anatomical features affecting liquid penetrability in three hardwood species. Wood and Fiber 7:256-263.

Tiemann, H. D. 1906. Effect of moisture upon the strength and stiffness of wood. U.S. Dep. Agric. For. Serv., Bull. 70. 144 p.

Tiemann, H. D. 1951. Wood technology. 3rd. ed. 396 p. New York, N. Y.: Pitman Publ. Corp.

Urquhart, A. R., and N. Eckersall. 1932. The absorption of water by rayon. Textile Insti. 23:T163-T170.

U.S. Department of Agriculture, Forest Service. 1955. Wood Handbook. U.S. Dep. Agric. For. Serv., Agric. Handb. 72. 528 p. For. Prod. Lab., Madison, Wis.

U.S. Department of Agriculture, Forest Service. 1957. Special methods of seasoning wood. High temperature drying: its application to the drying of lumber U.S. Dep. Agric. For. Serv., For. Prod. Lab. Rep. 1665-1. 6 p.

U.S. Department of Agriculture, Forest Service. 1967. FPL '67 annual report of research at the Forest Products Laboratory, U.S. Dep. Agric. For. Serv., 38 p. U.S. For. Prod. Lab., Madison, Wis.

U.S. Department of Agriculture, Forest Service. 1974. Wood handbook: Wood as an engineering material, U.S. Dep. Agric. For. Serv., Agric. Handb. 72, rev. For. Prod. Lab., Madison, Wis.

Venkateswaran, A. 1970. Sorption of aqueous and nonaqueous media by wood and cellulose. Chem. Rev. 70(6):619-637.

Wahlgren, H. E. 1957. Tension wood in overcup oak. U.S. Dep. Agric. For. Serv., FPL. Rep. No. 2089. 15 p.

Wall, R. F. 1958. Process analysis by thermal conductivity. Ind. Eng. Chem. 50(12):69A-70A.

Wangaard, F. F. 1957. A new approach to the determination of fiber saturation point from mechanical tests. For. Prod. J. 7:410-416.

Wangaard, F. F., and L. A. Granados. 1967. The effect of extractives on water-vapor sorption by wood. Wood Sci. and Technol. 1:253-277.

Ward, J. C., and J. G. Zeikus. 1974. Methane formation in living trees: a microbial origin. Sci. 184:1181-1183.

Wartluft, J. L. 1977. Weights of small Appalachian hardwood trees and components. U.S. Dep. Agric. For. Serv., Res. Pap. NE-366. 4 p.

Wengert, E. M. 1976. Predicting average moisture content of wood in a changing environment. Wood and Fiber 7:264-273.

Wheeler, E. A. 1981. Intervascular pitting in *Fraxinus americana* L. IAWA Bull. 2(4):169-174.

9

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CHAPTER 9

Physical Properties

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CHAPTER 9

Physical properties

Four chapters in this text describe physical and mechanical properties. Three are devoted to properties of major significance to converters and users of wood (i.e., specific gravity, chapter 7; wood water relationships, chapter 8; and mechanical properties, chapter 10). In this chapter, properties of lesser importance to many users have been grouped for discussion, i.e., color characterization, and electrical, thermal, friction, and acoustical properties.

9-1 COLOR CHARACTERIZATION

The main visible change observed in wood of trees is change in color. This can be the result of processes associated with aging (heartwood development), injury (formation of discolored wood), or both. The formation of heartwood, its proportions, and its variability are described in section 5-1. Discolored wood is discussed in this section.

The color of wood strongly influences its use. For example, manufacturers of paneling find that interior decorators are strongly attracted to the red flame grain of sweetgum figured heartwood, but are less interested in the sapwood of the species. Most purchasers of hardwood floors for residences prefer the warm tones of oak heartwood to the lighter shades of maple. Furniture manufacturers like the light-colored sapwood of hackberry, ash, and oak because they accept a variety of finishes in a range of shades from blonde to dark. Strong color variations, such as those frequently found in discolored red maple or in yellow-poplar heartwood, are undesirable in exposed furniture parts.

Particleboard and fiberboard purchasers, for reasons not entirely understood, prefer light-colored boards with no dark inclusions. Most pulp and paper manufacturers also seek light-colored woods to minimize bleaching costs.

Color, therefore, is an important attribute of wood; its characterization is difficult, however. Descriptions may be verbal, pictorial, or mathematical.

VERBAL DESCRIPTION

In older hardwoods (except sweetbay) heartwood is generally darker than sapwood and the color range among species is substantial (table 9-1). This is also true of central discolored wood, which is frequently called heartwood. In air-dry stemwood of 6-inch hardwoods grown on pine sites the range in color among species is less pronounced. There is little color difference between sapwood and heartwood in green and white ash, red maple, hickory, hackberry, sweetbay, sweetgum, and black tupelo (fig. 5-16).

PICTORIAL DESCRIPTION

Figures 5-4 through 5-15 are color photographs of stemwood of hardwoods grown on southern pine sites. Perhaps the most striking feature of these illustrations is the preponderance of light coloration ranging from white to light tan. Only some of the oaks (blackjack, post, southern red, water, and white) show dark tones of brown or gray.

Readers interested in color plates of heartwood of mature hardwoods will find illustrations in Southern Hardwood Lumber Manufacturers Association (n.d.) and U.S. Department of Agriculture, Forest Service (1956).

TABLE 9-1.—*Color of heartwood and sapwood in mature hardwoods*

Species	Heartwood (or discolored wood)	Sapwood
Ash, green and white......	(Brown)	Light colored, nearly white
Elm, American...........	Light brown, often tinged with red	Nearly white
Hackberry...............	Darker than sapwood	Pale yellow to greenish or grayish yellow
Hickory.................	Reddish (pale brown to reddish-brown in bitternut hickory)	White
Maple, red..............	(Light reddish brown frequently with a grayish cast; sometimes the gray is dark and pronounced)	Nearly white with a grayish or reddish tinge
Oak, all red species.......	Brown, with a tinge of red	Nearly white
Oak, all white species.....	Grayish brown	Nearly white
Sweetbay................	Heartwood not evident	Creamy white to light tan
Sweetgum...............	(Reddish brown, the darker grades frequently with dark streaks of pigment figure)	White, frequently with a pinkish tinge often discolored with blue sapstain
Tupelo, Black............	Light brownish gray	Light colored
Yellow-poplar............	Yellowish brown with greenish tinge, sometimes streaked with purple, green, black, blue, or red	White

MATHEMATICAL DESCRIPTION[1]

In 1931, the International Commission on Illumination developed the first criteria for instrumental color analysis (Judd 1933). Current American color measuring standards, based on the 1931 criteria, are outlined in ASTM Recommended Practice E308-66 (American Society for Testing and Materials 1976). The perceived color of an opaque specimen depends on the interaction of three factors: the illuminating source, the specimen, and the observer. Only the light illuminating a (non-fluorescing) specimen, not absorbed by the specimen, can be reflected to an observer for interpretation as the specimen color. Therefore, spectral quality of the illuminating source, the light absorption—reflection properties of the specimen, and interpretation of the reflected light by an observer, all contribute to apparent color of an object.

Three specific illuminating sources are defined and accepted as standard, designated A, B, and C, approximating respectively incandescent light, noon sunlight, and average daylight.

Illuminant spectral components and specimen reflectance characteristics can be measured readily. Average human observers can describe any color by matching it with various combinations of lights, each particular color requiring a unique combination of three standard spectral stimuli. Stimuli for a particular color are designated X, Y, and Z, and are termed the **tristimulus** values for that color. The Y stimulus was chosen specifically to parallel human perception of brightness, so that the Y tristimulus value represents light reflectance (**bright-** **ness**) for a specimen too. In order to simplify and clarify color specification each tristimulus value is divided by the sum of all three to yield trichromatic coefficients or **chromaticity coordinates**

$$\frac{X}{X+Y+Z} = x, \quad \frac{Y}{X+Y+Z} = y, \quad \frac{Z}{X+Y+Z} = z$$

whose sum equals unity ($x + y + z = 1$). Thus, any two coordinates (x and y are used most often) define the third and allow a color to be specified graphically in two dimensions on a **chromaticity diagram** which is delineated by coordinates of pure visible spectrum colors (fig. 9-1).

---

[1] Text under this heading is condensed with some revision, from Beckwith, J.R. III. Color of hardwoods grown on southern pine sites. Presentation at a symposium, "Utilization of hardwoods growing on southern pine sites", Alexandria, Louisiana, March 10-14, 1975. See also Beckwith (1979).

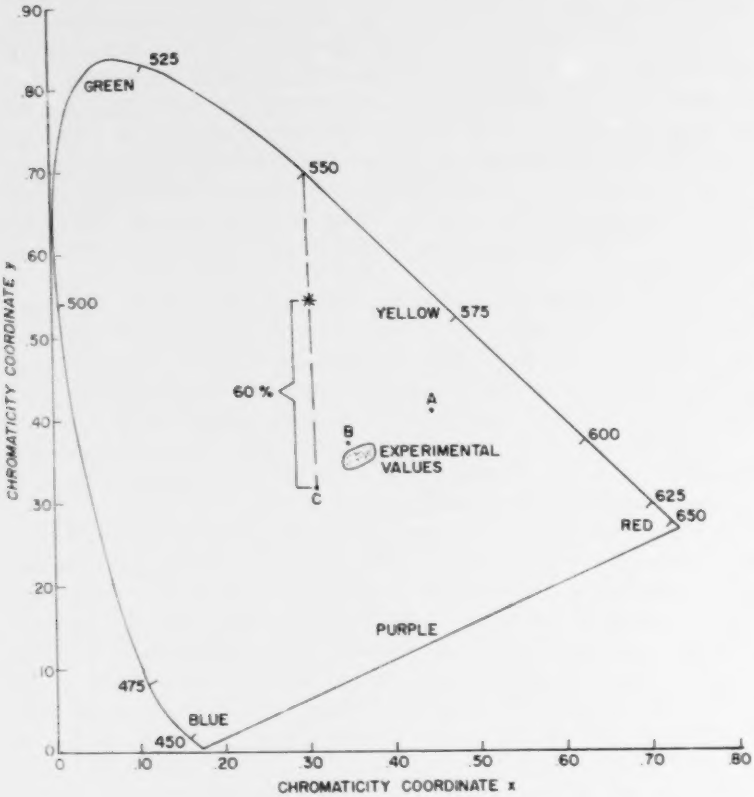

Figure 9-1.—Chromaticity diagram with standard illuminants A, B, and C located; values for 22 hardwoods plotted (circled); and an example point (*) illustrating determination of dominant wavelength (550 millimicrons) and color purity (60%) based on illuminant C. Under light source A or B, values would be different, i.e., those resulting from plotting computational lines through the appropriate light source. (Drawing after Beckwith 1979.)

In this diagram, all the colors lying within the solid boundary line, but above the triangle blue-Iluminant C-red, can be considered a mixture of Illuminant C and spectrum light of a certain wavelength. For example, in figure 9-1 the green * is a mixture of Illuminant C and spectrum light with a wavelength of 550 millimicrons. This wavelength is known as the **dominant wavelength.** Since this green * lies on a line which terminates at a pure spectrum color at one end and at the illuminant point at the other end, the sample is not as pure as the corresponding spectrum color. The **percent purity** of the green * is expressed as a percent of the distance between the light source and the curved perimeter—in this case 60 percent. Purple colors, falling below the lines BLUE-C-RED, require a different procedure (Hardy 1936), but none of the samples had colors falling in this area.

Two types of instruments are used to quantify color, colorimeters and spectrophotometers. Colorimeters utilize a light, a series of filters, and photodetectors to develop tristimulus specifications, chromaticity coordinates, and other data. Spectrophotometers measure reflectance of light from a specimen and a white (near 100% reflectance) standard at the same wavelength, yielding values of percent light reflected by the specimen relative to the standard for all visible wavelengths. From these reflectance data, standard color specifications can be calculated precisely for any defined illuminant.

Beckwith[1] has provided instrumental analysis of the color of hardwoods grown on southern pine sites (table 9-2); in his study, stemwood specimens were taken 6 feet above ground level from 10 trees (table 3-1) of each species. These specimens were cut to provide 2-inch-square transverse, radial, and tangential surfaces for analysis; 6 hours or less prior to analysis, surfaces were sanded with 80-grit and then 120-grit sandpaper and blown free of sander dust.

Among-species variation.—Because the specimens examined by Beckwith[1] included both heartwood (possibly discolored) and sapwood in most pieces they appeared quite variable in color as viewed by the eye. When color-scanned, they appeared quite variable in color as viewed by the eye. When color-averaged by the spectrophotometer, however, these differences were not so apparent. The chromaticity diagram (fig. 9-1), on which average coordinates (table 9-2) for each species are plotted, illustrates the small range in chromaticity coordinates among these species of apparently different color. Average color parameters determined on longitudinal surfaces of selected species of these 6-inch trees are compared to some published values for larger trees (Beckwith 1974) by plotting them on an expanded portion of a chromaticity diagram (fig. 9-2). A comparison of chromaticity coordinates for longitudinal surfaces of red and white oaks (fig. 9-3) illustrates the possibility of separating certain species on the basis of chromaticity coordinates. Color purity of post oak and white oak (29 and 30 percent respectively) was significantly higher than that of the nine red oaks (21 to 27 percent). Brightness of post oak and white oak (34 and 35 percent) was generally less than that of the red oaks which ranged from 25 to 47 percent and averaged 40 percent. Thus stemwood from the 6-foot level in small white oaks was less red, purer in color, and darker (less bright) than stemwood of red oaks of similar size.

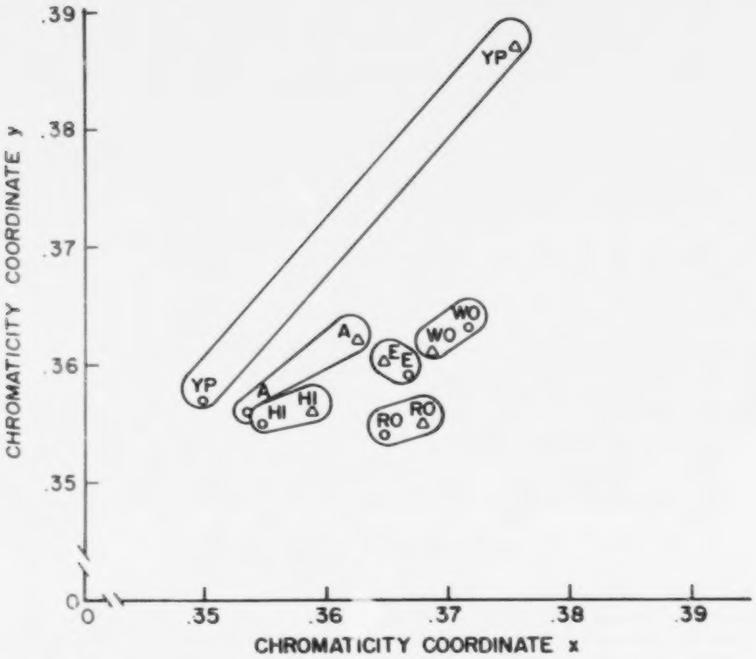

Figure 9-2.—Expanded portion of a chromaticity diagram comparing stemwood of 6-inch hardwood trees from southern pine sites (o) with wood from larger hardwoods of sawlog diameter (Δ). Symbols are as follows: ashes (A), elms (E), hickory (HI), red oaks (RO), white oaks (WO), and yellow-poplar (YP). (Drawing after Beckwith 1979.)

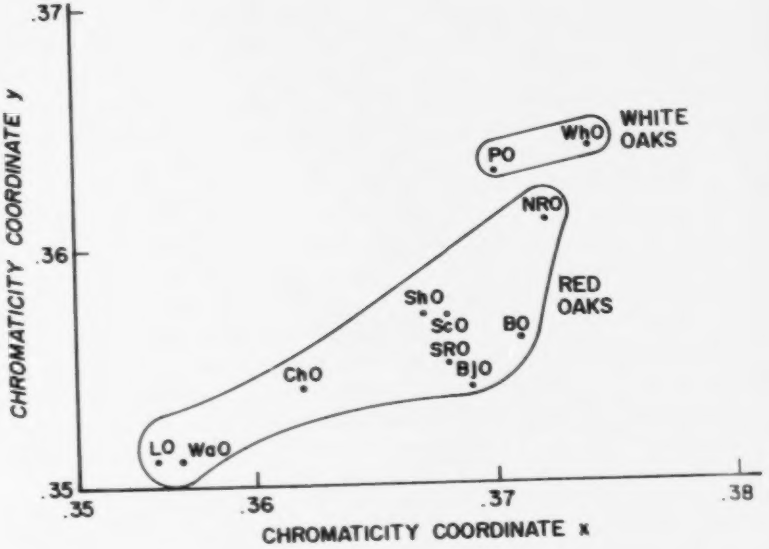

Figure 9-3.—Expanded portion of a chromaticity diagram comparing white oaks (post oak and white oak) to red oaks (black, blackjack, cherrybark, laurel, northern red, scarlet, Shumard, southern red, and water oaks). (Drawing after Beckwith 1979.)

TABLE 9-2.—*Color characteristics for transverse, radial, and tangential surfaces (sanded) of stemwood from 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2]

Species and surface	Dominant wavelength[3]	Color purity[3]	Brightness[3]	Chromaticity coordinates x	Chromaticity coordinates y	Chromaticity range index[4]
	Nanometers[5]	--------*Percent*	--------			
Ash, green						
Transverse . .	581 (1)	25 (6)	47 (9)	0.361	0.357	15
Radial	579 (1)	21 (5)	66 (7)	.351	.354	8
Tangential . .	579 (2)	21 (5)	64 (14)	.352	.354	9
Ash, white						
Transverse . .	581 (2)	26 (7)	44 (13)	.363	.358	18
Radial	579 (2)	22 (8)	64 (14)	.353	.355	20
Tangential . .	579 (2)	23 (7)	61 (14)	.355	.356	18
Elm, American						
Transverse . .	582 (4)	24 (2)	36 (22)	.363	.354	6
Radial	583 (5)	27 (11)	40 (34)	.371	.358	46
Tangential . .	582 (6)	28 (10)	41 (38)	.370	.358	30
Elm, winged						
Transverse . .	582 (7)	25 (5)	39 (32)	.365	.356	14
Radial	579 (3)	25 (7)	61 (22)	.360	.360	17
Tangential . .	580 (8)	27 (8)	53 (35)	.365	.361	32
Hackberry						
Transverse . .	579 (1)	18 (8)	42 (12)	.346	.348	22
Radial	577 (3)	19 (9)	61 (15)	.346	.351	34
Tangential . .	578 (4)	20 (10)	60 (29)	.347	.354	37
Hickory						
Transverse . .	582 (3)	28 (5)	43 (16)	.369	.360	12
Radial	579 (3)	22 (2)	63 (18)	.355	.356	3
Tangential . .	580 (3)	22 (5)	61 (10)	.355	.354	8
Maple, red						
Transverse . .	583 (5)	18 (8)	45 (16)	.350	.344	19
Radial	580 (2)	17 (4)	68 (11)	.344	.344	6
Tangential . .	580 (3)	17 (6)	64 (16)	.344	.345	5
Oak, black						
Transverse . .	584 (4)	26 (5)	29 (6)	.370	.353	11
Radial	583 (6)	26 (6)	38 (26)	.370	.356	17
Tangential . .	583 (4)	27 (6)	38 (16)	.371	.356	17

See footnotes at end of table.

TABLE 9-2.—*Color characteristics for transverse, radial, and tangential surfaces (sanded) of stemwood from 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2]—Continued

Species and surface	Dominant wavelength[3]	Color purity[3]	Brightness[3]	Chromaticity coordinates x	Chromaticity coordinates y	Chromaticity range index[4]
	Nanometers[5]	--------*Percent*	--------			
Oak, blackjack						
Transverse . .	584 (3)	23 (3)	21 (11)	.364	.349	4
Radial	584 (5)	25 (8)	26 (19)	.368	.353	16
Tangential . .	584 (3)	26 (8)	23 (18)	.370	.354	16
Oak, cherrybark						
Transverse . .	583 (2)	24 (8)	29 (14)	.365	.352	16
Radial	581 (3)	24 (9)	52 (19)	.359	.354	29
Tangential .	582 (2)	24 (12)	41 (24)	.364	.354	50
Oak, laurel						
Transverse . .	582 (3)	22 (6)	30 (19)	.357	.350	15
Radial	582 (5)	21 (7)	45 (28)	.356	.351	17
Tangential . .	582 (3)	21 (7)	41 (16)	.356	.350	17
Oak, northern red						
Transverse . .	584 (3)	26 (4)	27 (10)	0.370	0.356	7
Radial	582 (7)	27 (7)	42 (9)	.369	.360	29
Tangential . .	583 (2)	29 (10)	38 (18)	.374	.361	40
Oak, post						
Transverse . .	581 (6)	25 (5)	29 (15)	.363	.357	6
Radial	581 (2)	29 (9)	33 (10)	.370	.363	26
Tangential . .	581 (4)	28 (10)	35 (24)	.369	.362	28
Oak, scarlet						
Transverse . .	584 (2)	26 (6)	30 (6)	.369	.355	14
Radial	582 (2)	26 (5)	44 (13)	.366	.357	12
Tangential . .	583 (3)	27 (4)	42 (8)	.369	.357	8
Oak, Shumard						
Transverse . .	583 (3)	26 (3)	31 (9)	.369	.355	4
Radial	582 (2)	26 (7)	45 (20)	.366	.357	19
Tangential . .	582 (2)	26 (8)	44 (18)	.367	.357	21
Oak, southern red						
Transverse . .	583 (3)	23 (4)	29 (10)	.363	.350	5
Radial	583 (2)	26 (4)	36 (18)	.368	.355	5
Tangential . .	583 (4)	26 (6)	36 (13)	.367	.354	8

See footnotes at end of table.

TABLE 9-2.—*Color characteristics for transverse, radial, and tangential surfaces (sanded) of stemwood from 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2]—Continued

Species and surface	Dominant wavelength[3]	Color purity[3]	Brightness[3]	Chromaticity coordinates		Chromaticity range index[4]
				x	y	
	Nanometers[5]	--------*Percent*--------				
Oak, water						
Transverse . .	583 (3)	21 (5)	26 (12)	.359	.349	8
Radial	582 (3)	22 (8)	44 (29)	.358	.351	17
Tangential . .	582 (4)	21 (8)	44 (18)	.356	.350	20
Oak, white						
Transverse . .	583 (3)	28 (2)	22 (8)	.371	.359	2
Radial	582 (2)	29 (4)	35 (8)	.373	.363	6
Tangential . .	582 (4)	30 (4)	34 (12)	.374	.364	6
Sweetbay						
Transverse . .	579 (2)	23 (8)	49 (24)	.356	.357	26
Radial	577 (3)	22 (8)	66 (12)	.352	.358	18
Tangential . .	578 (2)	21 (6)	64 (21)	.350	.356	12
Sweetgum						
Transverse . .	582 (1)	18 (4)	40 (21)	.349	.346	6
Radial	580 (2)	19 (4)	54 (21)	.349	.348	8
Tangential . .	581 (2)	19 (5)	49 (18)	.350	.348	10
Tupelo, black						
Transverse . .	580 (3)	22 (6)	43 (25)	.355	.355	16
Radial	578 (3)	21 (4)	62 (12)	.351	.356	5
Tangential . .	579 (2)	23 (7)	50 (23)	.355	.357	15
Yellow-poplar						
Transverse . .	578 (3)	19 (6)	48 (15)	.346	.352	13
Radial	577 (2)	21 (8)	60 (16)	.349	.356	26
Tangential . .	577 (3)	22 (10)	59 (22)	.350	.357	21

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[1] Data are from Beckwith (see text footnote [1]).

[2] Wood sampled at 6-foot height in stem and analyzed at 6-percent moisture content; each value is the average for 10 trees sampled Southwide.

[3] Values in parentheses show range in statistic.

[4] Chromaticity range index = (range in x) (range in y) (100,000).

[5] A nanometer is 10^{-9} meter.

Within-species variation.—To describe color variability between 6-inch trees of these species, Beckwith[1] tabulated ranges in dominant wave length, color purity, and brightness, and computed a chromaticity range index (range in x times range in y times 100,000 (table 9-2). Species with minimum and maximum between-tree variability were as follows:

	Between-tree variability	
Parameter and surface	Minimum	Maximum
Dominant wave length		
Transverse	Green ash Hackberry Sweetgum	Winged elm
Radial	Green ash	Northern red oak
Tangential	Black tupelo Cherrybark oak Green ash Northern red oak Shumard oak Sweetbay Sweetgum White ash	Winged elm
Color purity		
Transverse	American elm White oak	Cherrybark oak Hackberry Red maple Sweetbay
Radial	Hickory	American elm
Tangential	Scarlet oak White oak	Cherrybark oak
Brightness		
Transverse	Black oak Scarlet oak	Winged elm
Radial	Green ash	American elm
Tangential	Scarlet oak	American elm
Chromaticity range-index		
Transverse	White Oak	Sweetbay
Radial	Hickory	American elm
Tangential	Red maple	Cherrybark oak

Davis and Beals (1977ab) used a spectrophotometer to analyze tangential surfaces of 202 pieces of **sweetgum.** The veneer and lumber specimens, which came from larger trees than those studied by Beckwith, measured 1 inch square and about ⅛-inch thick; they had unsanded knife-cut surfaces (sanding increased light absorption). Dominant wavelength varied from 578 to 590 millimicrons (fig. 9-4). Purity ranged from about 9 percent to 47 percent; these ranges suggest dominant wavelengths and purities slightly greater than those for smaller trees (table 9-2) of this species.

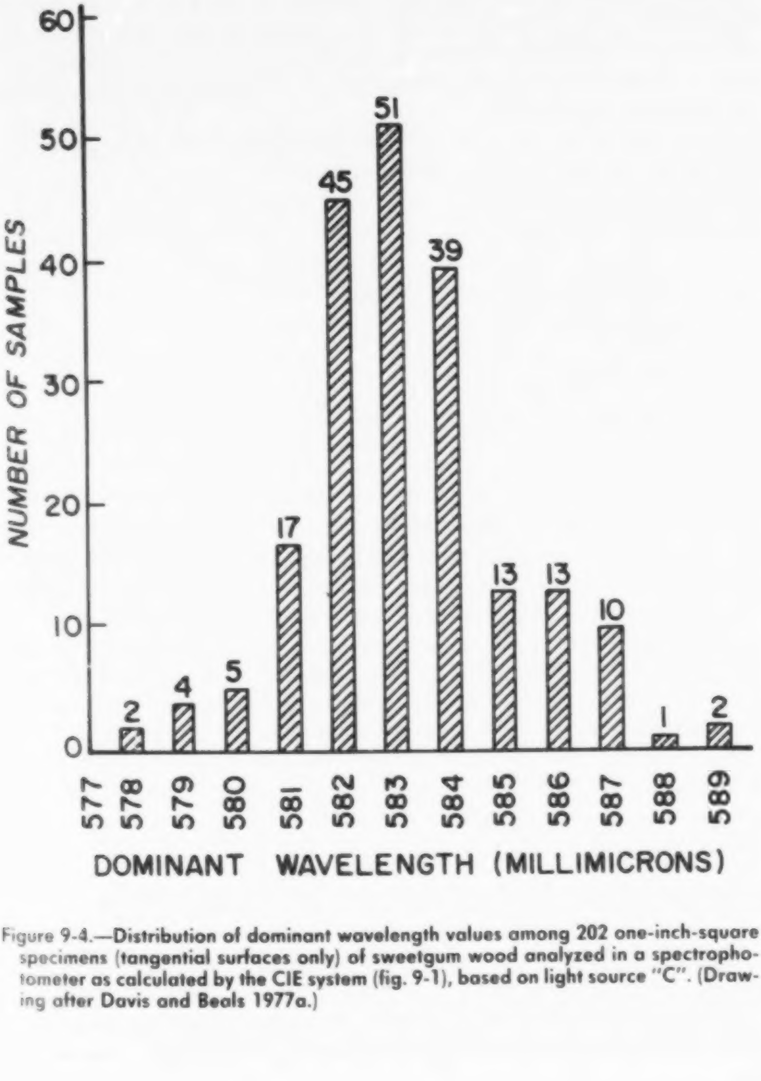

Figure 9-4.—Distribution of dominant wavelength values among 202 one-inch-square specimens (tangential surfaces only) of sweetgum wood analyzed in a spectrophotometer as calculated by the CIE system (fig. 9-1), based on light source "C". (Drawing after Davis and Beals 1977a.)

Transverse, radial, and tangential surfaces.—Among the samples studied by Beckwith, only in cherrybark oak and winged elm were there significant differences in **dominant wavelength** among the three surfaces. All surfaces were the same in American elm, black tupelo, blackjack oak, post oak, southern red oak, and yellow-poplar.

In 12 of the species, all surfaces had the same **color purity.** In the remaining 10, one surface had lower color purity as follows:

Species	Surface with least color purity
Ash, green	Tangential (or radial)
Ash, white	Radial
Elm, American	Transverse
Hickory	Tangential (or radial)
Oak, blackjack	Transverse
Oak, northern red	Transverse
Oak, post	Transverse
Oak, southern red	Transverse
Oak, white	Transverse
Yellow-poplar	Transverse

Only in black tupelo were all three surfaces the same **brightness.** In four species (black oak, blackjack oak, scarlet oak, and winged elm) none of the three surfaces had the same brightness. For all species, except black tupelo, transverse surfaces had significantly lower brightness than the other two surfaces.

Conclusions.—Instrumental color analysis, while useful in definition and separation of homogeneous colors, appears inadequate to describe the intermixed colors of wood surfaces. An "average" color for the scanned area is described even when several specific homogenous colors are present. To more adequately describe color of wood samples, a means to scan the smaller homogeneously colored areas of such samples and to express their relative color and proportional area will have to be developed.

DISCOLORED WOOD

The major transitions during heartwood formation—cell death, depletion of nutrients, and deposits in cells with darkening of tissues—also occur in formation of **discolored wood** associated with wounds. Discolored wood, in its earlier stages, often closely resembles true heartwood, and is frequently classified as such.

Discolored wood is formed as a response to the exposure of wood tissue to air and/or infection; its formation involves both oxidation and the deposit of phenols and other wood components (Shigo and Hillis 1973). Such discoloration spreads rather rapidly up and down the tree, much more slowly around its girth and very little radially outward into newer growth rings. There is little inward spread from shallow scars and birdpecks, but when the wound source is a broken branch stub the discoloration spreads rapidly to the pith through branch stub tissues. Thus discolored wood from a branch stub is confined to the part of the bole existing when the branch died, but a succession of such injuries during the life of the tree can result in a central core of discolored wood closely resembling heartwood.

Discolored wood probably is a manifestation of defense barriers set up by the tree against invading microorganisms. In its early stages it may or may not contain bacteria and non-hymenomycetous fungi; darker colors form where such invaders are present. If the tree is vigorous and the wound is small the discoloration may stop at this stage without decay. In less vigorous trees, especially where wounds are severe, decay fungi become established, degrading the cell wall substances and opening the way to many other organisms which compete for remaining portions of the tissues.

Wounds that expose primarily the xylem immediately under the bark include logging damage, animal or bird wounds, and fire wounds. After such wounding, discoloration may be contained or limited by mechanical barriers of plugged vessels formed around affected tissues. In those species capable of doing so, tyloses are formed; in other species the vessels are plugged with gummy extractives. Such plugs begin to form in red maple within a few days after wounding. After injury of the active living cambium, a circumferential barrier tissue featuring thick-walled rounded cells and diminished vessel volume may be formed to act as a partition between wood formed before and after wounding. Such partitions not only limit discoloration, but may be the major site of **shakes** or separations along growth rings (Shigo and Hillis 1973). Readers interested in the compartmentilization of discoloration and decay in trees will find Shigo and Marx (1977), a well-illustrated exposition of the subject.

Configuration of discoloration.—The literature contains limited analyses of the occurrence and variability of color in stemwood of hardwoods grown on southern pine sites. Red maple, black oak, northern red oak, white oak, and sweetgum have been studied, however. For discussions focussed on northern hardwoods, readers are referred to Shigo and Larson (1969) and Shigo and Marx (1977).

Shigo (1965) dissected 324 **red maple** sprouts from 72 clumps and found that branch stubs were more important infection courts for discoloration and decay organisms than were parent stumps. Discolored areas contain higher concentrations of K, Mn, Ca, Mg, and Na than adjacent bright wood (Safford et al. 1974). External indicators of defect (discoloration) that are located above the stump are more useful than indicators located at stump level. Because red maple does not naturally develop colored heartwood (Shigo 1975), such external indicators of discolored wood are useful to the processor who desires logs of uniform light coloration (fig. 9-5).

Shigo (1972) also studied patterns of discoloration in **white oak** and **northern red oak** associated with 22-year-old basal fire wounds and mechanical wounds inflicted during subsequent salvage operations. He found that columns of discolored and decayed wood advanced farthest along the sapwood-heartwood boundary present at the time of wounding. The discolored and decayed tissues associated with the wounds were confined to tissues present when the wounds occurred. The heartwood cylinder constricted abruptly below the root collar. Heartwood formation was retarded around wounds.

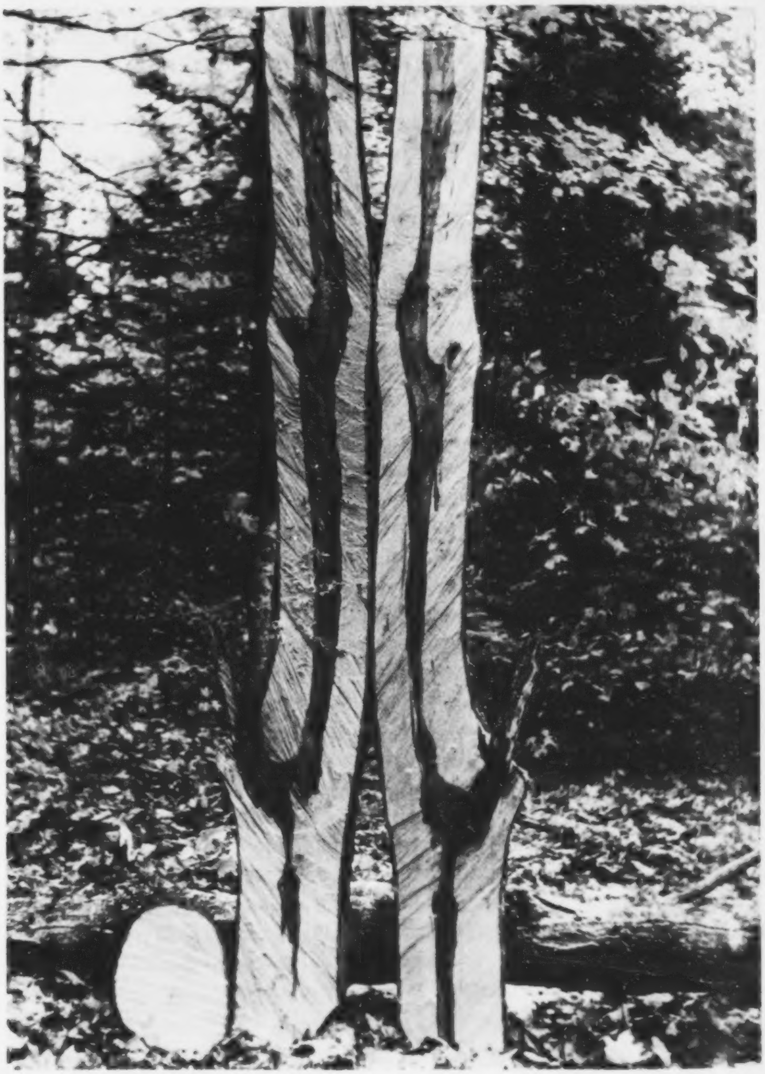

Figure 9-5.—Dissected sugar maple (*Acer saccharum* Marsh.) with base free of wounds and discolored wood. The column of discoloration from the stub of a low branch that recently died dwindles toward the base, but joins above with a wider column of discoloration from the older stub above, where the processes are more advanced. These discolored tissues are not heartwood. Wood formed after the upper stub died is free of discoloration. This pattern of discoloration is also typical of red maple. (Photo from Shigo and Larson 1969).

Sachs et al. 1966 concluded from studies of **black oak** and **northern red oak** that the dark stains forming at the sapwood-heartwood boundary of these species appear to be different from mineral stains and dark discolorations associated with injured sapwood. The darkening of stained oak heartwood is by an excessive production of pigmented compounds which appear to originate in the ray parenchyma cells and may be similar to the complex polyphenols of normal heartwood. The staining substances move from the ray parenchyma to adjoining vessels, fibers and tracheids by pit membranes and plasmodesmata. Flow or diffusion of the staining compounds may block the pits and obstruct the movement of moisture, resulting in internal checking or honeycomb during seasoning.

In a breast-height sample of five vigorous dominant or codominant **sweetgum** trees aged 20 years or over, from each of 87 plots in Alabama, Hunter and Goggans (1968) found that 10 percent of the trees were 36 years of age or older and still showed no colored heartwood or discolored wood. In this study, the area of colored heartwood or discolored wood averaged 18.5 percent; the percentage did not vary with geographic location.

In **sweetgum** trees 30 to 60 years old growing in North Carolina and without major wounds, Shortle and Cowling (1978) found only nondiscolored sapwood with living parenchyma cells from cambium to pith; they concluded that the trees contained sapwood only and no heartwood. Discolored wood in these trees was invariably associated with major wounds. The discolored wood was reddish brown and varied from continuous columns of uniform color, usually associated with broken tops, to discontinuous irregular columns. In both sweetgum and yellow-poplar, tissues formed after wounding were free of discoloration; superficial wounds inflicted during summer months resulted in formation of a thin sheet of intensely discolored wood on the exposed wound surface within 1 month after wounding; deep wounds yielded columns of discolored wood.

Davis and Beals (1977ab) analyzed transverse sections from the lower (fluted) end of butt logs from 132 **sweetgum** trees of saw-timber size in east-central Alabama; they also examined veneer peeled from 250 butt logs for indications of origin of discoloration.

Fifteen percent of the transverse sections exhibited no discoloration attributable to wounding. Fifty-nine percent of the sections exhibited less than 10-percent such discoloration (figs. 9-6, 9-7). Twenty-six percent had 10-percent or more discoloration (figs. 9-8, 9-9).

Origin of most minor central discoloration columns was limb stubs (fig. 9-7). Most partial-ring discoloration was caused by bird peck (fig. 9-6), and a slight amount by wood borers (fig. 9-8). Only two of the sections exhibited discoloration from fire wounds. Extensive discoloration probably results from a progression of different causes (fig. 9-9).

Davis and Beals found that central stain columns resulting from broken limbs occupied approximately the same cross-sectional areas at both ends of 16-foot logs, as well as at all intervening sections. Only slight differences in percentage of discoloration were detected when entire merchantable stems were cut and measured. Rapid longitudinal movement of stain fungi apparently contributes to this uniformity.

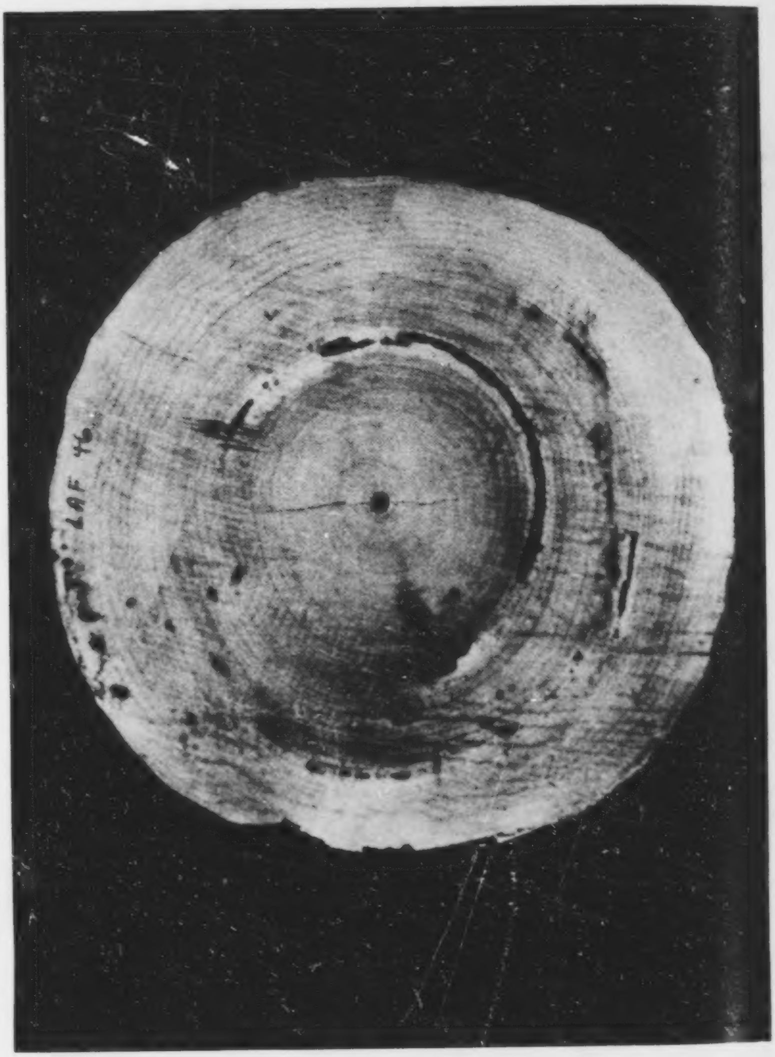

Figure 9-6.—Transverse section of sweetgum exhibiting 1.6-percent discoloration, mostly in a narrow band conforming to a growth ring. A minute core of stain surrounds the pith. Bird pecks caused the semi-circular band of discoloration and the flecks and bars in outer growth rings. (Photo from Davis and Beals 1977b.)

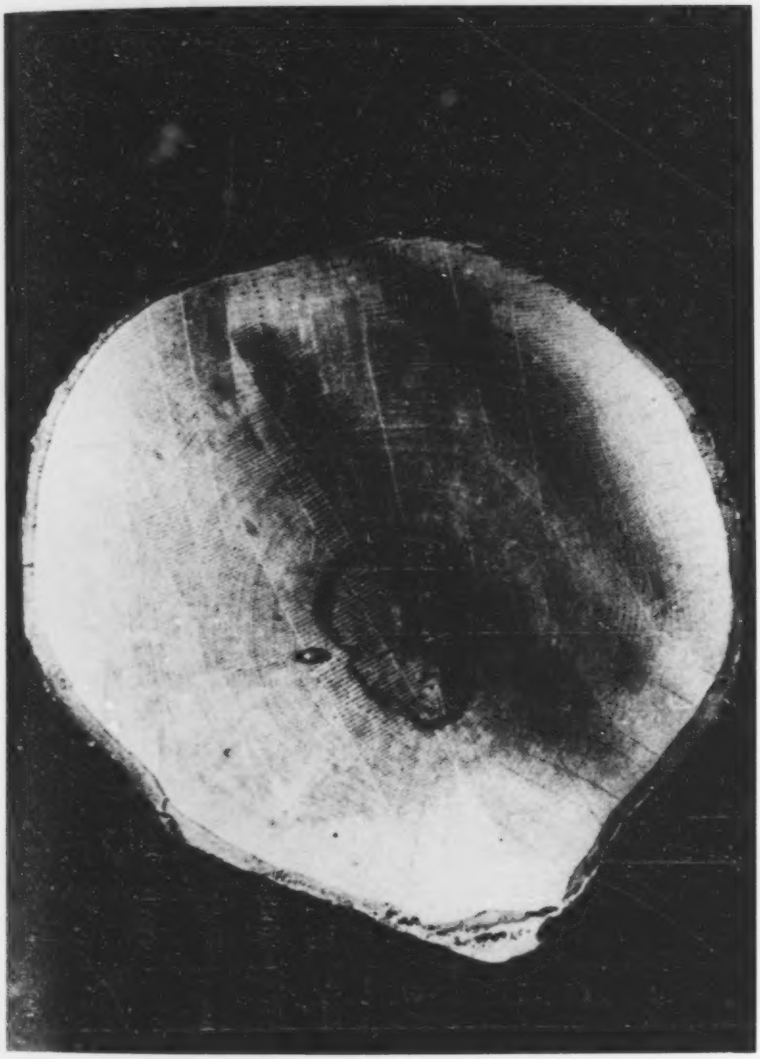

Figure 9-7.—Central column of discoloration in sweetgum (6.2-percent of cross-sectional area) typical of stains initiated at limb stubs. (Photo from Davis and Beals 1977b.)

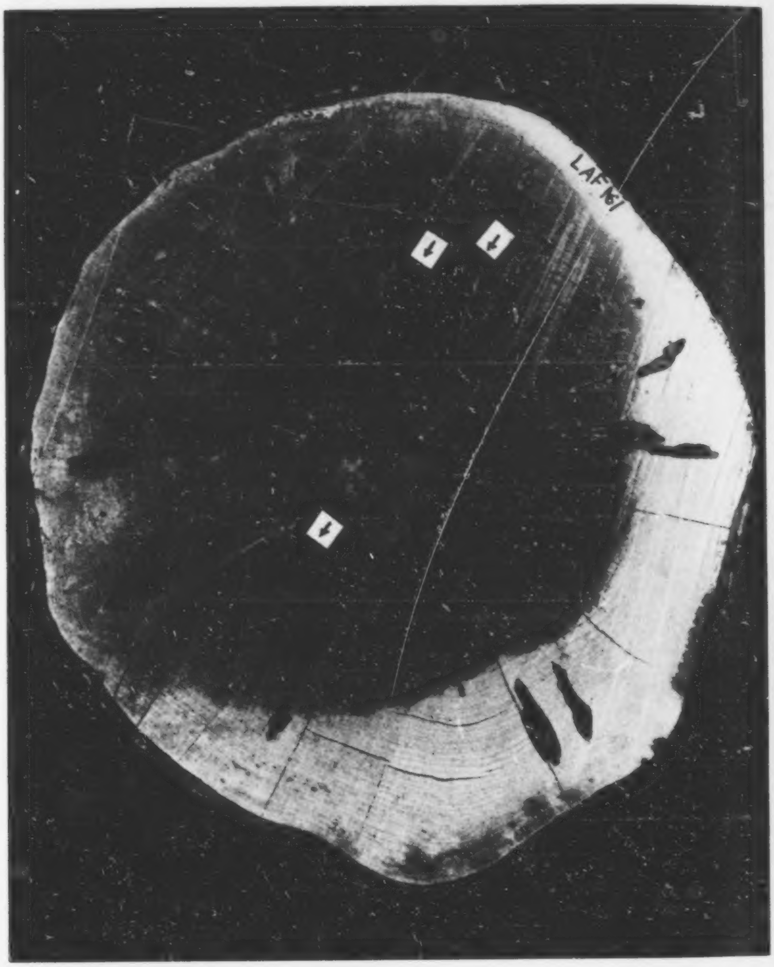

Figure 9-8.—Discoloration in sweetgum. The lightly shaded area (about 70% of the cross section), commercially classed as heartwood, probably originating at branch stubs higher in the tree. The smaller patches, mostly with dark outlines, (±8.7%) are areas of discolored wood induced by wood boring insects. Arrows identify tunnels. (Photo from Davis and Beals 1977b.)

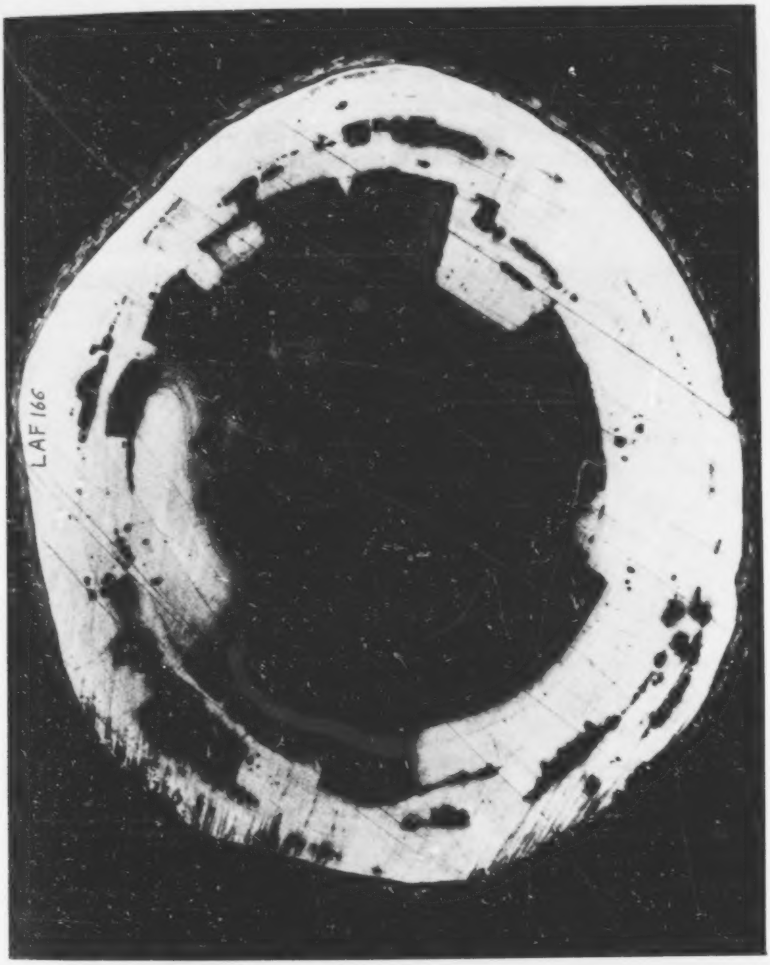

Figure 9-9.—Complex core of discoloration (45.3-percent of cross-sectional area) in sweetgum attributable to broken limbs, bird peck, insect wounds, and perhaps other causes. (Photo from Davis and Beals 1977b.)

Although all wood in existence at time of limb death is susceptible to ultimate invasion of stain fungi, outward movement is slight except towards wounds that occur later. In the Davis and Beals study, stain from bird pecks eventually coalesced with smaller central stain columns associated with limb stubs; this process may result in large complex stain columns (fig. 9-9). Such massive stain columns have irregular margins, often limited along radial planes by resistant tissues (fig. 9-10).

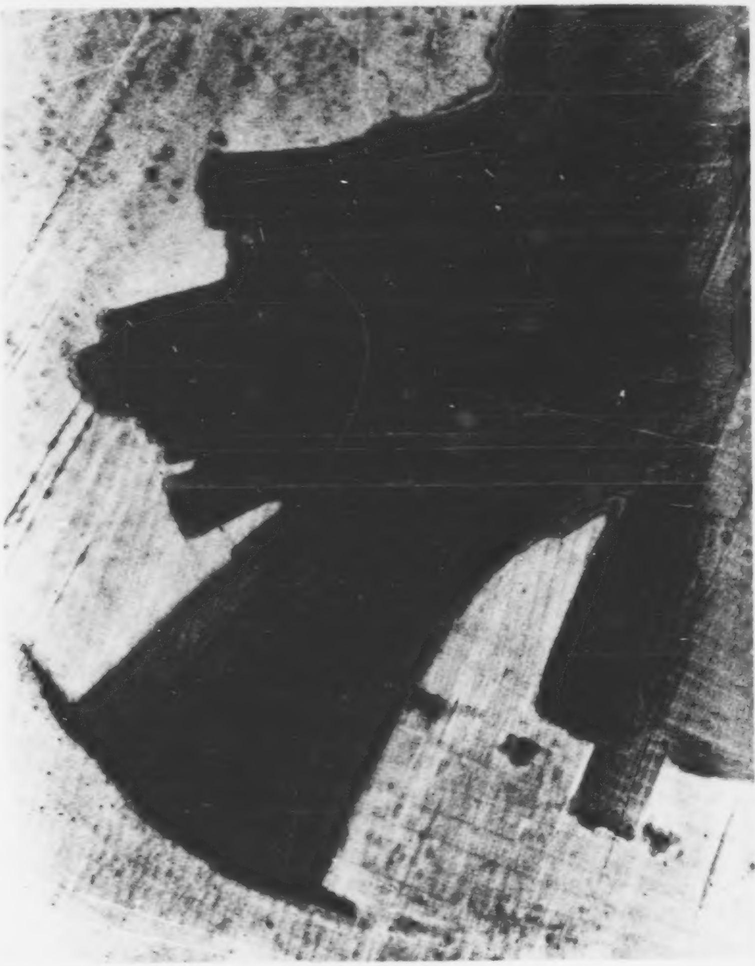

Figure 9-10.—Irregular margin of a stain column viewed in a transverse section of sweetgum. Stain was initiated at various depths, and has radially oriented boundaries. (Photo from Davis and Beals 1977b.)

Stain columns originating from beetle bore holes in sweetgum indicate that expansion in the longitudinal direction is very rapid; radial expansion is slow, and tangential expansion is almost nil. The L:R:T expansion ratio appears to be about 300:12:1.

Davis and Beals (1977ab) found no meaningful correlations between percent internal discoloration in sweetgum trees and tree age, growth rate, or average bark thickness. They concluded, however, that rapid height growth, small limbs, and early self-pruning of lower limbs create conditions that minimize internal discoloration in sweetgum.

Shortle and Cowling (1978) found that discolored wood in **yellow-poplar** trees studied in North Carolina was most commonly associated with basal wounds caused by fire, logging, and cutting or breakage of one or more stems in a sprout cluster. Both sapwood and heartwood were discolored in wounded yellow-poplar trees.

Significance of discoloration.—Hepting et al. (1952) have provided strength (toughness) analyses of discolored **yellow-poplar**; their results on this species probably have some applicability to the other southern hardwoods. In their study, test pieces measuring ½-inch wide by 5 inches long were cut from bright and discolored veneer 1/24- to 3/16-inch thick, rotary-peeled at two Appalachian mills.

Normal heartwood, which varied from bright light green to a pale tan and was distinguishable from discolored wood by these distinctive colors and by their uniformity, was not significantly weaker than sapwood.

Discolored wood tested included yellow-green, gray, lavender, black, dark green, red, purple, purple-brown, buff, brown (not rot), and brown (rot). Causes of the discolorations included fire, sap stain, blue-butt, insect bore holes, branch stubs and rot. **Blue-butt** is perhaps the most prevalent coloration of yellow-poplar. It extends upwards from the base of large trees and usually runs out within 16 feet of the stump cut. It may involve all of the wood radially to within a few inches of the bark, and there is a sharp line of demarcation between colored and bright (un-colored) wood. Generally, where the discolored and bright wood meet, there is a band of purplish or greenish brown wood. Inside this zone the wood may be colored reddish, purple, or lavender, with some areas dark green. Fresh logs that are blue on the ends are often green inside. These colors are attributable to a uniform coloration of cell walls and dark deposits in ray cells. Such wood is frequently water-soaked and consequently very heavy.

Hepting et al. (1952) reached conclusions as follows:

- Blue-butt wood is not significantly lower in strength than bright wood; warping and smoothness are the same as in bright wood.
- Veneers with general discolorations (from stem wounds) in shades of lavender, purple, and dark green are as tough as bright wood, but have a slightly higher specific gravity. Warping and surface smoothness is the same as in bright wood. Brown wood, however, is weaker than bright wood.

- Streaks of discoloration resulting from insect bore holes, (purple, green, or black) often extend a foot or more either way from the holes and contain wood significantly less tough (7-percent) than bright wood. Warping of streaked portions is different from bright wood, so that there is often a hump perpendicular to the grain where veneer sheets are streaked.
- Short black streaks, seldom more than a few inches long and believed to result from fire scars, are weaker perpendicular to the grain than bright wood and cause warp similar to that observed in veneer streaked from insect bore holes. Black-streaked wood is not, however, weaker in toughness than bright wood.
- Broad streaks of discolored wood generally 1 to 3 inches wide are generally greenish, greenish-brown, or purplish in color and appear unassociated with insect damage or obvious defect. Specific gravity in these streaks is normal, but such veneer streaks from one of the two mills studied had wood 13-percent weaker in toughness than normal wood. Veneer showing such broad streaks tended to split at the border of bright and discolored wood.
- All rotted veneer was discolored in shades of brown, usually either a rust brown or dark brown, and often mottled with small open pockets. The surface of veneer cut from rotted wood, even if only in the incipient stage of decay, is almost always rough. Even wood with only incipient decay is somewhat lower in specific gravity and is significantly weaker than bright wood.

Hepting et al. (1952) concluded that all veneer colored any shade of pure brown should be culled; they further note that discolorations causing weakness almost always impart a rough surface to rotary-peeled veneer.

Luxford and Wood (1953, figs. 7 through 14) have provided graphs relating color of yellow-poplar to specific gravity and to the following strength properties: modulus of rupture, modulus of elasticity, work to maximum load, toughness, maximum crushing strength, stress at proportional limit, side hardness and shear strength. The graphs indicate that all of these strength properties are closely correlated to specific gravity, i.e., those colors—principally brown and heavy gray sapstain—that are associated with low specific gravity, contain weak wood.

Detection of discoloration.—Electric currents generated by polarizing metal electrodes and measured in microamperes have been found by Tattar (1974) to increase progressively from clear to discolored to decayed wood in red maple and northern red oak. Using this principle, which was investigated by several researchers in the years 1957-1972, Skutt et al. (1972) demonstrated a prototype instrument and Shigo and Shigo (1974) developed a commercial meter for detection of discoloration and decay in living trees and utility poles. The meter carries a probe for insertion into a 3/32-inch hole bored 8 to 12 inches deep into the wood to be analyzed. In the "Shigometer®", ohms resistance to pulsed electric current of the wood in contact with the probe tip is measured. When the probe tip passes from sound wood to discolored or decayed wood, there is an abrupt decrease in resistance correlated with the degree of discoloration or decay. For accounts of users' experience with the meter, see Shortle et al. (1978) and Piirto and Wilcox (1978).

Gray-brown chemical stain[2]—From time to time, southern hardwood lumber manufacturers encounter a troublesome and costly staining problem—troublesome because this stain develops in chemically dipped as well as undipped sapwood lumber, and costly because, unlike blue stain, it may show up only after final lumber surfacing in the plant. This nonfungus, gray to brown chemical stain develops rapidly at temperatures above 50°F during prolonged wet seasons. It frequently occurs in soft maple, hackberry, hickory, red oak, and dogwood, where it resembles blue stain, but is not as visible on rough surfaces because surface fibers usually dry rapidly enough to prevent stain development. The wood immediately beneath, however, remains wet long enough to allow the chemical stain to develop. The stain probably results from oxidation and enzymatic action on certain materials stored in wood cells.

The stain is present only in ray parenchyma cells; because of the proximity of rays to each other, however, entire surfaces appear stained. Since chemical stain and fungus stain are alike in appearance and develop under similar conditions, a means of differentiating between the two is useful. Concentrated oxalic acid bleaches out chemical stain, but not fungus stain.

The most effective control means is rapid seasoning of sapwood lumber. Air seasoning practices are inadequate during poor drying weather.

Unless low-temperature seasoning (below 50°F) is feasible, Clark (1957) recommends preseasoning heat treatments such as steaming. Steaming freshly sawn wood arrests the stain development permanently. Seasoning wood at temperatures below 50°F prevents stain development, but sapwood so seasoned may stain later if rewetted.

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[2] Text under this heading is condensed from Bois (1970), with some additions.

Price (1982) found that the most effective methods of preventing gray-brown chemical stain in 2.5-in squares sawn from freshly felled hackberry were atmospheric steaming for 60 min before air-drying, or prompt conventional kiln-drying without steaming. A 30-min initial steaming cycle was more effective in preventing stain than air-seasoning. A kiln schedule with high initial temperature (155°F) was about as effective as a 30-min atmospheric steaming treatment. A 30-min initial heating cycle in air at 212°F prior to air-seasoning had no benefit. To be effective, steaming or kilning must be initiated promptly after trees are felled and sawn.

Forced-air drying may also effectively prevent chemical stain in some species. Experimental work with predryers (Vick 1965, 1968) indicates that sweetgum and yellow-poplar can be dried in a few days with little or no degrade. Rucker and Smith (1961) have described industrial forced air drying of hackberry and *Magnolia* spp. to avoid chemical stains. Dense hardwoods such as oak and hickory, however, cannot be dried at rapid rates without serious checking and splitting.

McMillen (1975) observed that interior graying and sticker staining of hard maple (*Acer saccharum* Marsh.) were associated with slow air drying under mild conditions or improperly controlled kiln drying. Fungus infection was found in some specimens with interior graying. McMillen (1976) concluded that a low-temperature low relative humidity kiln schedule produced white 4/4 or 5/4 lumber; a moderate-temperature, moderate relative humidity schedule produced the light orange-yellow color normal in hard maple. Kiln malfunctions causing unwanted high-humidity conditions produced reddish-brown lumber.

Iron tannate stains.—Surfaces of red oak parquet flooring bonded directly to on-ground concrete slab subfloors have become stained black, sometimes with a bluish or greenish cast. Vick and Taras (1969) concluded that the stain results from a chemical reaction between minute particles of iron (derived from steel wool, wood fiber, or abrasives used) and the natural tannins in red oak wood in the presence of moisture. Recommendations to avoid such staining included:

- Dry and cure concrete slabs, whether suspended or on-ground, before installing hardwood flooring. On-ground slabs should be protected from diffusion of ground moisture into the slab and into the flooring.
- Allow sufficient time for the building interior to dry, and keep relative humidity low by proper ventilation or heating.
- Avoid use of sanding and finishing materials containing iron, if possible.
- Follow manufacturer's instructions for installation and finishing.

Pinking of hickory sapwood.—A pink to reddish-brown chemical sapwood stain sometimes occurs during 7- to 9-day kilning of green hickory sapwood for handle stock. Because white tool handles are preferred by tool buyers, Hopkins and Kelso (1951) developed extended "non-pinking" schedules for small blanks (1.5 by 2 inches in cross section and 32 to 38 inches long), as follows:

Moisture content	Dry-bulb temperature	Wet-bulb temperature
Percent	*°F*	*°F*
• For blanks previously air-dried, under roof, to 20-percent moisture content		
20 to 15.	105	86
15 to 8.	115	79
• For green blanks		
Green to 40.	105	99
40 to 30.	105	92
30 to 20.	105	80
20 to 8.	115	79

With these schedules, kiln time for previously air-dried blanks is about 7 days and for green blanks about 24 days.

Photo-induced discoloration.—Exposure of wood to light causes discoloration, usually darkening it; the reactions are complex (see Koch 1972, p. 629-636). Umehara et al. (1979), for example, found that ultraviolet light darkens northern red oak and makes it reddish, but visible light rays lighten it and reduce its redness; consequently, when irradiated by both ultraviolet and visible light rays at the same time, the color of northern red oak wood changes only slightly. They also found that when 0.25 percent $NaNO_2$ was spread on northern red oak wood, or when the wood was soaked in a solution where 20 percent H_2O_2 and 0.02-percent diethyl-p-phenylenediamine sulfate were mixed in equal quantities, photo-induced discoloration was effectively reduced or prevented.

9-2 ELECTRICAL PROPERTIES[3]

The most important electrical properties of wood are its conductivity, dielectric constant, and dielectric power factor.

The **conductivity** of a material determines the current that will flow when the material is placed under a given voltage gradient. The **dielectric constant** of a nonconducting material determines the amount of electric potential energy, in the form of induced polarization, that is stored in a given volume of the material when that material is placed in an electric field. The **power factor** of a nonconducting material determines the fraction of stored energy that is dissipated as heat when the material experiences a complete polarize-depolarize cycle.

Electrical properties of wood are important in products such as crossarms and poles for powerlines, linemen's tools, and in the heat-curing of adhesives in wood products by high-frequency electric fields. Moisture meters for wood utilize the relation between electrical properties and moisture content to estimate the moisture content.

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[3] Introductory text under the major headings in this section is taken from the Wood Handbook (U.S. Department of Agriculture, Forest Service 1974, p. 3-21 and 3-22) with addition of information pertinent to hardwoods grown on southern pine sites.

ELECTRICAL CONDUCTIVITY

The electrical conductivity of wood varies slightly with applied voltage and approximately doubles for each temperature increase of 10°C. Electrical conductivity or its reciprocal, **resistivity**, varies greatly with wood moisture content, especially below the fiber saturation point. As moisture content increases from near zero to fiber saturation, the electrical conductivity increases (resistivity decreases) by 10^{10} to 10^{13} times. Resistivity is about 10^{14} to 10^{16} ohm-meters for ovendry wood and 10^{3} to 10^{4} ohm-meters for wood at fiber saturation. As the moisture content increases from fiber saturation to complete saturation of the wood structure, the further increase in conductivity is erratic and smaller, generally less than a hundred-fold.

Resistivity is a material property independent of sample size. Resistance, however, depends on sample length and cross-sectional area, as well as material. Thus resistance (ohms) is computed by dividing the product of resistivity (ohm-meters) and specimen length (meters) by specimen cross-sectional area (square meters). Figure 9-11 illustrates the change in resistance along the grain with moisture content, based on tests of many domestic species. Variability between test specimens is illustrated by the shaded area. Ninety percent of the experimental data points fall within this area. The resistance values were obtained with a standard moisture meter electrode at 80°F. Conductivity is greater along the grain than across the grain (about double) and slightly greater in the radial direction than in the tangential direction.

Okoh (1976) provided data on longitudinal resistivity of wood and radial resistivity of bark of 21 hardwoods from pine sites (table 3-1) when subjected to a direct current gradient of 50 volts; wood specimens measured 3 mm along the grain, and matching bark specimens of the same species were about 1.5 mm in the radial direction.

Resistivity (at 25°C) related to moisture content.—Okoh (1976) found that the logarithms of resistivities (log r) of wood (and bark) specimens were related to the logarithms of their moisture contents (log M) as follows:

$$\log r = A - (B \log M) \qquad (9\text{-}1)$$

With data from all species pooled, resistivity of stembark is not significantly different from that of stemwood (fig. 9-12), although differences may be significant in some species. Data on bark resistivity of all 21 species are tabulated in chapter 13. Data for wood of these species (table 9-3) indicate that hackberry has lowest resistivity (most conductivity) and yellow-poplar has highest resistivity (least conductivity), as follows:

Statistic and moisture content	Average	Minimum (hackberry)	Maximum (yellow-poplar)
Log r			
12% MC	8.238	7.419	8.826
18% MC	6.394	5.619	6.918
Resistivity			
12% MC (ohm cm)	172.98×10^{6}	26.24×10^{6}	669.88×10^{6}
18% MC (ohm cm)	2.48×10^{6}	$.42 \times 10^{6}$	8.28×10^{6}

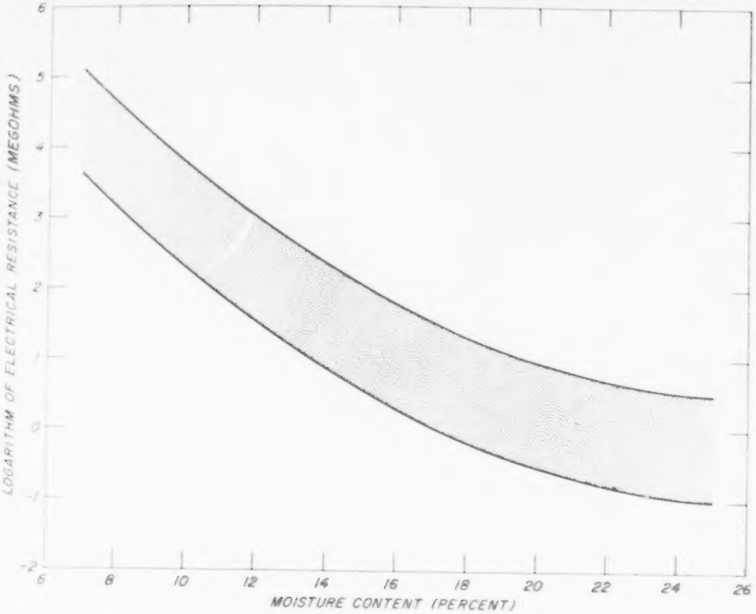

Figure 9-11.—Electrical resistance observed using a typical needle-type moisture meter electrode, aligned so the current flows parallel to the grain. Ninety percent of test values of many United States wood species are represented by the shaded area. (Drawing after U.S. Department of Agriculture, Forest Service 1974.)

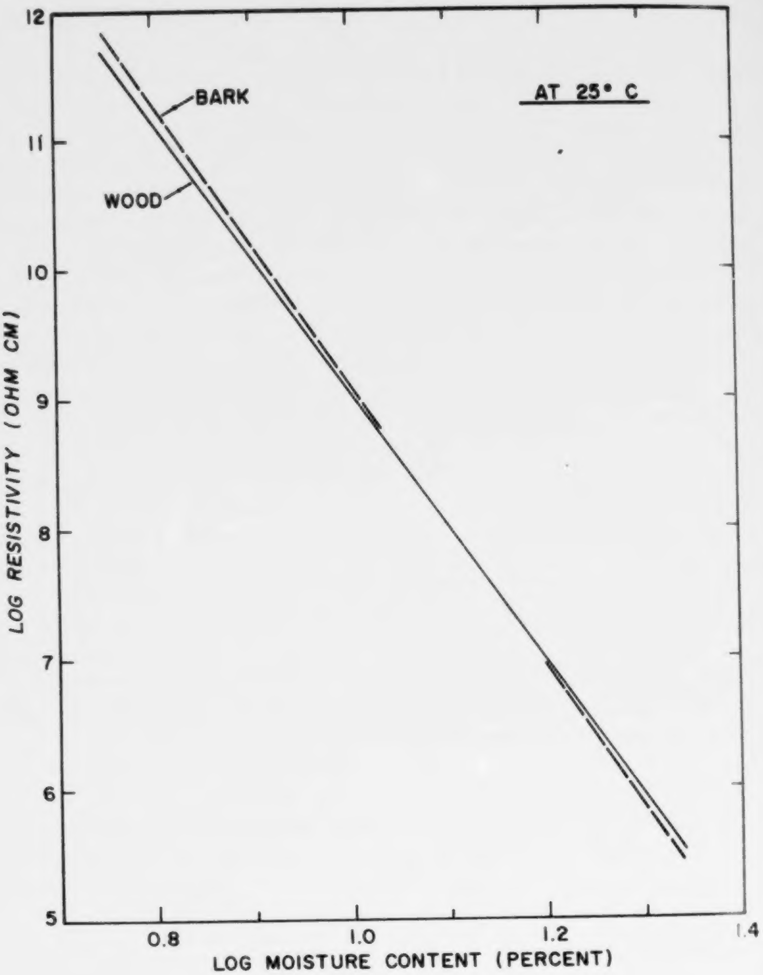

Figure 9-12.—Pooled data (average) for 21 species of hardwoods grown on southern pine sites showing logarithm of resistivity at 25°C of stemwood (longitudinal) and stembark (radial) as related to the logarithms of their moisture contents. (Drawing after Okoh 1976, p. 1971.)

TABLE 9-3.—*Logarithm of resistivity (at 25°C) parallel to grain of stemwood from 6-inch trees of 21 hardwood species grown on southern pine sites, at 12- and 18-percent moisture contents, and regression coefficients for the equation: log resistivity, ohm-cm = A-(B log moisture content, percent)* (Okoh 1976, p. 149)

Species	Regression coefficients A	Regression coefficients B	Correlation coefficient R	Logarithm of resistivity at 12% MC	Logarithm of resistivity at 18% MC
Ash, green	19.634	10.747	0.999	8.036	6.144
Ash, white	19.234	10.265	.999	8.156	6.349
Elm, American	19.298	10.450	.999	8.021	6.180
Elm, winged	18.323	9.721	.980	7.832	6.120
Hackberry	18.451	10.222	.993	7.419	5.619
Hickory	20.389	11.215	.999	8.286	6.311
Maple, red	19.258	10.211	.999	8.239	6.441
Oak, black	19.456	10.266	.999	8.377	6.570
Oak, blackjack	20.438	11.115	.999	8.443	6.486
Oak, cherrybark	18.806	9.776	.997	8.256	6.534
Oak, chestnut	—	—	—	—	—
Oak, laurel	19.765	10.934	.999	7.966	6.040
Oak, northern red	19.395	10.267	.999	8.314	6.506
Oak, post	20.610	11.276	.999	8.441	6.456
Oak, scarlet	19.396	10.199	.999	8.389	6.593
Oak, Shumard	19.344	10.390	.999	8.131	6.301
Oak, southern red	19.355	10.228	.999	8.318	6.517
Oak, water	19.153	10.293	.999	8.045	6.232
Oak, white	20.950	11.297	.999	8.758	6.769
Sweetbay	18.983	10.030	.999	8.158	6.392
Sweetgum	19.559	10.162	.998	8.592	6.802
Tupelo, black	—	—	—	—	—
Yellow-poplar	20.518	10.834	.998	8.826	6.918
Average	19.539	10.471	.998	8.238	6.394
Standard deviation	.696	.473		.312	.289
Coefficient of variation	3.564	4.522		3.782	4.515

In wood from trees of sawlog size, Langwig and Skaar (1975) found slightly different relations between percent moisture content and resistivity (r) as follows:

Species	Equation
Ash, white	$\log r = 17.141 - 8.915 \log M$
Hickory, shagbark	$\log r = 17.967 - 9.120 \log M$
Oak, northern red	$\log r = 17.657 - 8.811 \log M$
Yellow-poplar	$\log r = 17.229 - 8.271 \log M$

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Resistivity related to temperature.—The logarithm of resistivity parallel to the grain is linearly related to the reciprocal of absolute temperature of the specimen (fig. 9-13). Resistivity at high temperature is therefore less than at low temperature; thus, conductivity is greatest at high temperature. Data on the temperature-moisture content relationship for longitudinal resistivity of stemwood of 22 species are provided in table 9-4.

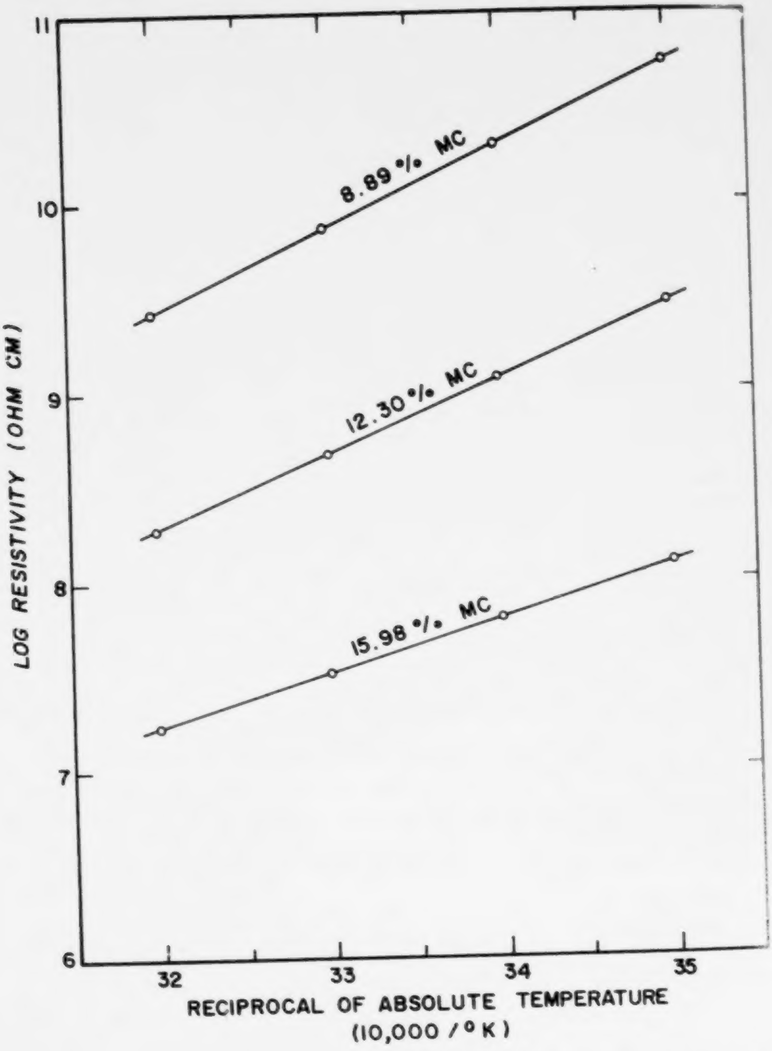

Figure 9-13.—Logarithm of resistivity parallel to the grain of stemwood from 6-inch yellow-poplar trees grown on southern pine sites related to the reciprocal of absolute temperature. (Drawing after Okoh 1976, p. 73.)

TABLE 9-4.—*Activation energy and logarithm of resistivity (ohm-cm) parallel to grain, at four temperatures and three moisture contents, of stemwood of 6-inch trees of 22 hardwood species grown on southern pine sites* (Okoh 1976, pp. 151-152)

Species and moisture content (percent)	Resistivity				Activation energy E
	39.4°C	29.9°C	21.0°C	12.6°C	
	------------------------*Log ohm-cm*------------------------				*Cal/mole*
Ash, green					
9.8	8.445	8.917	9.381	9.848	21.381
12.7	7.513	7.897	8.287	8.666	17.602
16.4	6.240	6.494	6.779	7.086	12.916
Ash, white					
9.5	8.702	9.169	9.642	10.111	21.504
12.7	7.649	8.012	8.409	8.804	17.677
16.3	6.610	6.918	7.217	7.541	14.155
Elm, American					
9.7	8.441	8.895	9.364	9.816	21.023
13.3	7.515	7.891	8.265	8.642	17.192
16.3	6.305	6.583	6.876	7.180	13.351
Elm, winged					
9.9	8.334	8.815	9.268	9.747	21.471
13.0	7.504	7.878	8.256	8.641	17.339
16.9	6.184	6.457	6.723	7.042	13.004
Hackberry					
9.5	7.840	8.315	8.802	9.252	21.622
12.5	7.138	7.480	7.821	8.166	15.675
16.0	5.853	6.095	6.355	6.633	11.902
Hickory					
10.2	8.551	8.884	9.377	9.830	19.821
13.4	7.301	7.655	8.015	8.375	16.397
17.2	6.170	6.449	6.677	7.008	12.548
Maple, red					
9.1	9.019	9.489	9.946	10.385	20.853
12.3	7.854	8.236	8.614	8.985	17.250
15.9	6.401	6.696	6.961	7.281	13.298
Oak, black					
9.2	8.856	9.344	9.797	10.267	21.446
12.2	7.826	8.206	8.615	8.993	17.901
16.0	6.520	6.837	7.141	7.474	14.491
Oak, blackjack					
9.9	8.495	8.994	9.478	9.957	22.291
12.9	7.529	7.930	8.328	8.741	18.468
16.5	6.345	6.658	6.960	7.291	14.372

Table continued on page 678.

TABLE 9-4.—*Activation energy and logarithm of resistivity (ohm-cm) parallel to grain, at four temperatures and three moisture contents, of stemwood of 6-inch trees of 22 hardwood species grown on southern pine sites* (Okoh 1976, pp. 151-152)—Continued

Species and moisture content (percent)	Resistivity				Activation energy E
	39.4°C	29.9°C	21.0°C	12.6°C	
	Log ohm-cm				*Cal/mole*
Oak, cherrybark					
9.3	8.528	9.023	9.456	9.960	21,633
13.1	7.619	7.993	8.383	8.754	17,371
16.0	6.312	6.632	6.933	7.242	14,145
Oak, laurel					
9.3	8.478	8.970	9.456	9.927	22,107
12.4	7.537	7.920	8.316	8.713	17,952
16.2	6.135	6.447	6.743	7.078	14,297
Oak, northern red					
9.4	8.971	9.443	9.855	10.302	20,157
12.7	8.048	8.441	8.802	9.153	16,816
16.3	6.685	7.019	7.309	7.536	13,013
Oak, post					
9.5	8.917	9.399	9.833	10.270	20,565
12.8	7.888	8.256	8.614	8.978	16,615
16.6	6.530	6.864	7.168	7.501	14,722
Oak, scarlet					
9.5	8.796	9.265	9.665	10.107	19,827
12.0	8.065	8.440	8.815	9.179	16,997
15.9	6.622	6.933	7.219	7.522	13,672
Oak, Shumard					
9.3	8.669	9.157	9.641	10.104	21,919
12.4	7.733	8.128	8.521	8.896	17,756
16.2	6.307	6.633	6.931	7.260	14,444
Oak, southern red					
9.8	8.713	9.161	9.577	9.995	19,509
12.8	7.915	8.271	8.630	8.995	16,471
16.2	6.566	6.852	7.132	7.443	13,317
Oak, water					
9.6	8.538	9.016	9.483	9.938	21,362
12.3	7.486	7.867	8.257	8.636	17,579
16.2	6.200	6.517	6.806	7.127	14,054

TABLE 9-4.—*Activation energy and logarithm of resistivity (ohm-cm) parallel to grain, at four temperatures and three moisture contents, of stemwood of 6-inch trees of 22 hardwood species grown on southern pine sites* (Okoh 1976, pp. 151-152)—Continued

Species and moisture content (percent)	Resistivity				Activation energy E
	39.4°C	29.9°C	21.0°C	12.6°C	
	Log ohm-cm				*Cal/mole*
Oak, white					
10.1	8.657	9.077	9.497	9.877	18,666
13.0	7.984	8.327	8.704	9.026	16,027
16.8	7.119	7.374	7.630	7.939	12,429
Sweetbay					
9.4	8.766	9.225	9.680	10.139	20,933
12.4	7.783	8.145	8.538	8.871	16,728
16.2	6.527	6.848	7.111	7.434	13,652
Sweetgum					
9.6	8.985	9.453	9.896	10.344	20,683
13.1	7.860	8.221	8.587	8.951	16,649
17.3	6.531	6.822	7.089	7.410	13,280
Tupelo, black					
9.5	8.794	9.254	9.722	10.181	21,185
12.8	7.780	8.147	8.506	8.901	17,035
16.8	6.403	6.716	7.000	7.318	13,862
Yellow-poplar					
8.9	9.414	9.867	10.293	10.722	19,903
12.3	8.198	8.559	8.919	9.285	16,562
16.0	7.236	7.512	7.795	8.091	13,031

Resistivity related to grain direction.—Transverse resistivity for six of the pine-site hardwoods evaluated (sweetgum, black tupelo, southern red oak, white oak, green ash, and American elm) averaged about 2.3 times greater than that parallel to the grain. The variation of transverse resistivity in both radial and tangential directions, with temperature and moisture content are shown in table 9-5, and summarized (for 25°C) in table 9-6. Comparable data are not available for the other 17 species listed in table 3-1.

TABLE 9-5.—*Transverse-to-grain activation energy and logarithm of resistivity (ohm-cm), at four temperatures and three moisture contents, of stemwood of six species of hardwoods grown on southern pine sites* (Okoh 1976, p. 153).

Species-direction and moisture content (percent)	Resistivity				Activation energy E
	39.4°C	29.9°C	21.0°C	12.6°C	
	Log ohm-cm				Cal/mole
Ash, green - tangential[1]					
9.0	9.113	9.577	10.010	10.431	20,081
11.4	8.331	8.730	9.140	9.538	18,440
17.2	6.496	6.822	7.141	7.476	14,915
Elm, American - radial[2]					
8.9	9.393	9.864	10.312	10.696	19,927
11.4	8.509	8.900	9.291	9.693	18,037
16.9	6.672	7.019	7.359	7.708	15,782
Oak, southern red - radial					
8.8	9.097	9.577	10.044	10.478	21,107
11.2	8.301	8.723	9.154	9.579	19,511
16.9	6.286	6.666	7.028	7.413	17,116
Oak, southern red - tangential					
9.3	9.223	9.637	10.024	10.380	17,656
12.3	8.327	8.674	9.022	9.354	15,695
16.7	6.932	7.235	7.502	7.815	13,344
Oak, white - radial					
9.9	9.042	9.483	9.890	10.302	19,161
11.9	8.466	8.846	9.235	9.637	17,844
17.5	6.716	7.075	7.390	7.724	15,277
Sweetgum - radial					
8.4	9.776	10.231	10.690	11.119	20,529
11.9	8.549	8.924	9.304	9.684	17,319
17.1	6.961	7.296	7.602	7.931	14,720
Sweetgum - tangential					
8.7	9.918	10.366	10.842	11.210	19,911
11.7	8.764	9.163	9.528	9.912	17,437
17.2	7.034	7.350	7.679	8.002	14,799
Tupelo, black - radial					
8.8	9.549	9.979	10.394	10.852	19,785
11.8	8.457	8.829	9.196	9.579	17,085
16.9	6.919	7.230	7.554	7.865	14,473
Tupelo, black - tangential					
9.4	9.482	9.909	10.316	10.763	19,450
11.5	8.692	9.083	9.480	9.866	17,938
16.9	7.045	7.373	7.685	8.020	14,813

[1] Tangential means field tangential to grain (direction C in fig. 9-23).

[2] Radial means field radial to grain (direction D in fig. 9-23).

TABLE 9-6.—*Comparison of longitudinal (r_L) and transverse (r_X) resistivities at 25°C of stemwood from six species of hardwoods grown on southern pine sites* (Data from Okoh 1976, p. 87)[1]

Species	At 12% MC		At 18% MC	
	Longitudinal	Transverse	Longitudinal	Transverse
	Megohm-cm			
Ash, green	135.52	322.85	1.45	5.27
Elm, American	151.71	484.17	2.26	6.82
Oak, southern red	269.77	445.65	3.52	8.02
Oak, white	421.70	672.98	15.96	21.98
Tupelo, black	218.27	776.25	3.31	13.00
Sweetgum	413.05	970.51	5.40	16.29
Average	268.34	612.07	5.32	11.90
Standard deviation	125.07	239.52	5.38	6.43
RT_X/RT_L	2.28		2.24	

[1] See table 3-1 for description of trees

Correction factor for DC moisture meters.—Electric moisture meters using pin-type electrodes and DC current measure resistance in the vicinity of the electrode (R_S), and not the longitudinal resistivity (r_L) The relationship between the two is as follows (Okoh 1974[4]):

$$\log R_S = 0.34 + \log r_L \qquad (9\text{-}2)$$

James (1975b) has related electrical resistance along the grain of nine pine-site hardwoods, measured between typical moisture-meter needle electrodes, to moisture contents from 7 to 25 percent (table 9-7). He found substantial variation among species, e.g., at 10-percent moisture content the resistance of *magnolia* spp. (2,040 megohms) was nearly twenty times that of American elm (110 megohms).

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[4] Okoh, I.K.A. 1974. Relating the resistance of wood by needle-type electrodes to resistivity by geometrically spaced flat electrodes. Unpublished report. SUNY Coll. of Environ. Sci. and For., Syracuse, N.Y.

TABLE 9-7.—*Average electrical resistance along the grain of nine hardwoods, measured at 80°F between two pairs of needle electrodes 1-1/4 inches apart and driven to a depth of 5/16-inch, at different moisture contents* (James 1975b)

Moisture content (percent)	Ash,[1] white	Elm, American	Hickory[1] (spp.)	Magnolia[1] (spp.)	Oak,[2] northern red	Oak, white	Sweetgum	Tupelo,[2] black	Yellow[2] poplar
					Megohms				
7	12,000	18,000	—	43,700	14,400	17,400	38,000	31,700	24,000
8	2,190	2,000	31,600	12,600	4,790	3,550	6,460	12,600	8,320
9	690	350	2,190	5,010	1,590	1,100	2,090	5,020	3,170
10	250	110	340	2,040	630	415	815	1,820	1,260
11	105	45	115	910	265	170	345	725	525
12	55	20	50	435	125	80	160	275	250
13	28	12	21	205	63	42	81	120	140
14	14	7	11	105	32	22	45	58	76
15	8.3	3.9	6.3	56.2	18.2	12.6	25.7	27.6	43.7
16	5.0	2.3	3.7	29.5	11.3	7.2	15.1	13.0	25.2
17	3.2	1.5	2.3	16.2	7.3	4.3	9.3	6.9	14.5
18	2.0	1.0	1.5	9.1	4.6	2.7	6.0	3.7	8.7
19	1.3	.7	1.0	5.3	3.0	1.7	4.0	2.2	5.8
20	.9	.5	.7	3.1	2.1	1.2	2.6	1.4	3.8
21	.6	.4	.5	1.9	1.5	.8	1.8	1.0	2.6
22	.5	.4	.4	1.2	1.0	.6	1.3	.6	1.9
23	.4	.4	.4	.7	.8	.5	.9	.5	1.4
24	.4	.4	.4	.5	.6	.4	.6	.3	1.1
25	.4	.4	.4	.3	.5	.4	.5	.2	.9

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[1] Exact species not known.

[2] Values calculated from measurements on veneer.

If temperature of the wood measured is different from the temperature for which the meter is calibrated (usually 21.1°C) a correction factor must be applied to the reading, i.e., wood metered when hot will appear to have higher moisture content than actual. Okoh (1976, p. 161) gives correction factors as follows as average for the 22 species listed in table 9-4:

Wood moisture content	Percent moisture content correction per °C of wood temperature difference from meter calibration temperature
Percent	*Percentage points*
12	0.114
18	.118

At 12-percent moisture content, the range of correction factors is from 0.105 (hickory) to 0.125 (white ash); at 18-percent moisture content, the range is from 0.091 (winged elm) to 0.148 (white oak). For example, if white ash on removal from the kiln is metered at 50°C, whereas the meter is calibrated for 21°C, it must read 15.6-percent moisture content (12 + 29 × .125) if the wood is to actually contain 12-percent moisture content based on dry weight.

Langwig and Skaar (1975) computed temperature correction factors for resistance-type moisture meters measuring parallel to the grain of wood from trees of sawlog size; their data follow:

Species and wood moisture content	Percent moisture content correction per °C of wood temperature difference from meter calibration temperature
Percent	*Percentage points*
Ash, white	
12	0.121
18	.104
Hickory, shagbark	
12	.131
18	.133
Oak, northern red	
12	.131
18	.136
Yellow-poplar	
12	.130
18	.144
Average	
12	.128
18	.129

James (1975b, p. 19) has provided a chart applicable to wood species in general, from which true moisture contents can be derived from resistance type meter readings taken from −40 to +240°F.

Activation energy.—There is strong evidence that the conduction of electricity in cellulosic materials is **ionic,** i.e., it is proportional to the number of free ions in the substance, (Hearle 1953, Brown et al. 1963, and Lin 1965). Lin (1965) proposed a statistical distribution of charge carriers in wood, which was assumed to be in equilibrium at a given temperature. Thus, a given fraction of the ions, initially bound in ion-generating sites are released upon absorption of an energy, U; these dissociated ions must absorb enough energy to overcome a potential barrier, W, to become free ions. Lin related the sum of U and W to activation energy, E, which is the energy (calories per mole) to release one mole of bound ions to the free state. From a concept advanced by Clark and Williams (1933), the natural logarithm of resistivity can be expressed as follows:

$$\ln r = (E/RT) - K_1 \qquad (9\text{-}3)$$

where r is resistivity, R is the universal gas constant (R = 1.99 cals/mole degree), T is the absolute temperature in degrees Kelvin, and K_1 is a constant.

Equation 9-3 can be rewritten in terms of **activation energy**, E, by taking the derivative of both sides of equation 9-3 with respect to 1/T, as follows (K_1 is constant with respect to temperature):

$$d \ln r/d(1/T) = E/R - 0$$

therefore,

$$E = R(d \ln r/d(1/T))$$

and in terms of logarithm to the base 10,

$$E = 2.303\ R(d \log r/d(1/T)) \qquad (9\text{-}4)$$

If the resistivity of wood at some moisture content is measured at several temperatures, and log r is plotted against the reciprocal of the absolute temperature (1/T), the activation energy (E) can be computed from equation 9-4.

Okoh's (1976, p. 82) study indicated that the best relationship between activation energy and percent moisture content (MC) is of the form (fig. 9-14):

$$E = C - (D \log MC) \qquad (9\text{-}5)$$

where C and D are constants for each species. The mean activation energy over a temperature range from 12.6° to 39.4°C for the 22 hardwoods listed in table 9-4 (pooled data) is given by:

$$E = 51.46 - 31.24 \log MC \qquad (9\text{-}6)$$

where E is given in thousand calories per mole.

Relationship of wood density to resistivity.—Venkateswaran (1973), found density of wood (varied by compression) is related to resistivity (r) as follows:

$$\log r = \log A + (B/\text{density}^3) \qquad (9\text{-}7)$$

where A and B are constants, empirically derived.

Relationship of lignin content to resistivity.—A positive linear relationship has been found between acid-insoluble lignin content and DC conductivity of vacuum-dried woods, i.e., woods of lowest lignin content have least conductivity (Venkateswaran 1974). Since hardwoods have less lignin than softwoods, their conductivity is generally less than that of softwoods.

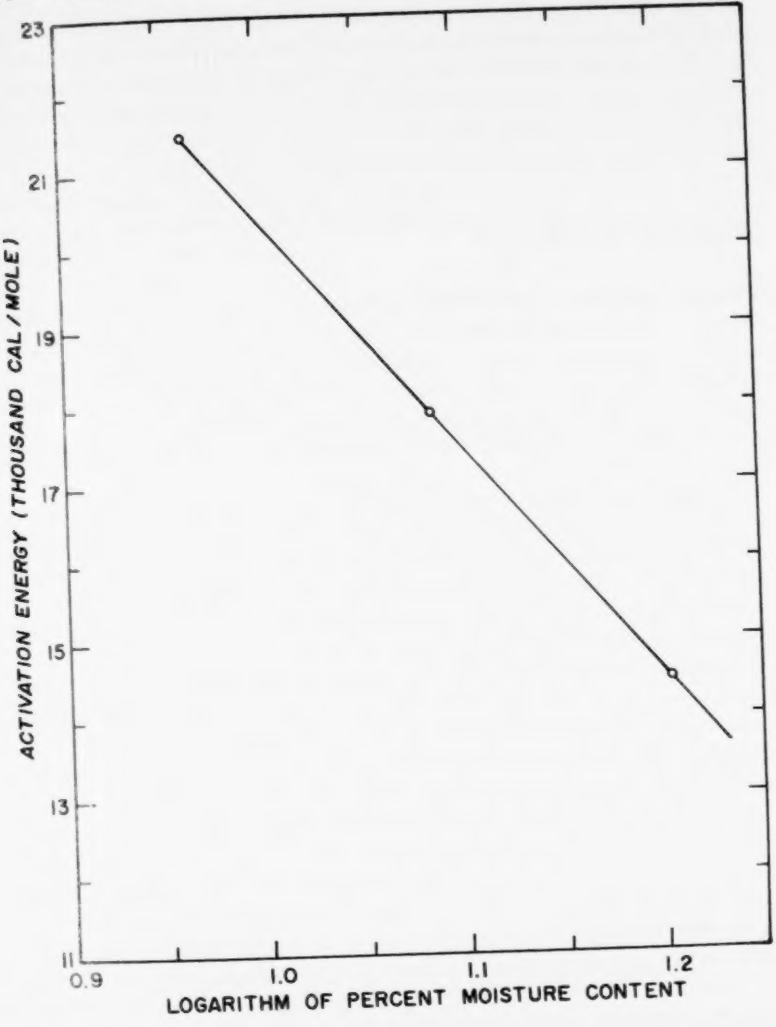

Figure 9-14.—**Activation energy over temperature range from 12.6° to 39.4°C (average 26°C) related to moisture content in wood of black oak (Drawing after Okoh 1976, p. 76.)**

Resistivity of carbonized wood.—Carbonization of wood greatly increases its conductivity. The logarithm of the resistivity of carbonized wood is linearly proportional to the temperature at which carbonized; thus, birch wood (*Betula* spp.) carbonized at 400°C had resistivity of about 1,000 × 10^6 ohm-cm at room temperature while that carbonized at 700°C had resistivity of only 1,000 ohm-cm (Beall et al. 1974).

Effect of impregnants on conductivity.—When wood contains abnormal quantities of water-soluble salts or other electrolytic substances, such as from preservative or fire-retardant treatment or prolonged contact with seawater, the electrical conductivity may be substantially increased. The increase is small when the moisture content of the wood is less than about 8 percent but becomes large rapidly as the moisture content exceeds 10 or 12 percent.

DIELECTRIC PROPERTIES[5]

Dielectric constant.—The dielectric constant is the ratio of the dielectric permittivity of the material to that of free space (which is unity); it is essentially a measure of the potential energy per unit volume stored in the material in the form of electric polarization when the material is in a given electric field. As measured by practical tests, the dielectric constant of a material is the ratio of the capacitance of a capacitor using the material as the dielectric, to the capacitance of the same capacitor using free space as the dielectric.

The dielectric constant of ovendry wood ranges from about 2 to 5 at room temperature, and decreases slowly but steadily with increasing frequency of the applied electric field. It increases as either temperature or moisture content increase, with a moderate positive interaction between temperature and moisture. There is an intense negative interaction between moisture and frequency: At 20 Hz the dielectric constant may range from 4 for dry wood to near 1,000,000 for wet wood; at 1 KHz, from 4 when dry to 5,000 wet; and at 1 MHz from 3 when dry to 100 wet. The dielectric constant is larger for polarization parallel to the grain than for across the grain. The dielectric anisotropy results principally from the macroscopic structure of wood—a composite of cellular substance and air (Kröner and Pungs 1952, 1953).

Dielectric power factor.—When a nonconductor is placed in an electric field, it absorbs and stores potential energy. The amount of energy stored per unit volume depends upon the dielectric constant and the magnitude of the applied field. An ideal dielectric releases all of this energy to the external electric circuit when the field is removed, but practical dielectrics dissipate some of the energy as heat. The power factor is a measure of that portion of the stored energy converted to heat. Power factor values always fall between zero and unity. When the power factor does not exceed about 0.1, the fraction of the stored energy that is lost in one charge-discharge cycle is approximately equal to 2π times the power factor of the dielectric; for larger power factors, this fraction is approximated simply by the power factor itself.

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[5] Text under this heading is taken from U.S. Department of Agriculture, Forest Service (1974, p. 3-22).

The power factor of wood is large compared to most inert plastic insulating materials, although in some, such as certain formulations of rubber, power factors are equally large. The power factor of wood varies from about 0.01 for dry low-density woods to as large as 0.95 for dense woods at high moisture levels. It is usually, but not always, greater along the grain than across the grain.

The power factor of wood is affected by several factors, including frequency, moisture content, and temperature. These factors interact in complex ways to cause the power factor to have maximum and minimum values at various combinations of these factors.

Readers desiring a review of dielectic properties of wood and cellulose will find Lin (1967) useful. James (1975a) has provided a tabulation of dielectric properties of white oak, Douglas-fir, and hardboard as related to temperature, frequency, moisture content, and grain orientation.

9-3 THERMAL PROPERTIES

An oak or hickory tool handle at 180°F can be grasped without undue discomfort, whereas an aluminum handle above 120°F is definitely uncomfortable to hold. For the same reasons, an oak or maple floor feels warmer than tile. These observations are manifestations of important thermal properties of wood, i.e., **specific heat** and **heat transmissivity** (Smith 1960). Other important thermal properties of wood are its **heat of combustion** and **coefficient of thermal expansion**. These properties influence both the processes by which wood is converted and the performance of finished wood products.

Data specific to the thermal properties of hardwoods on pine sites are unavailable. Lacking these data, values must be estimated from available statistics such as chemical constituents, specific gravity, and moisture content; relationships are presented from which such approximations can be developed.

SPECIFIC HEAT

The specific heat of wood is the heat capacity of a given mass of wood compared to the same mass of water at 15°C. Heat capacity of a material may be expressed as the number of calories required to raise 1 g 1°C in temperature. Because heat capacity of water at 15°C is 1 calorie per gram per degree C, heat capacity and specific heat are numerically equal.

Specific **heat of chemical constituents.**—The specific heat of wood is determined by the specific heat of its constituents and of the air contained within the lumens. McMillin (1970) found that the specific heats of alpha-cellulose, holocellulose, lignin, and extractives derived from loblolly pine were positive linear functions of temperature in the range 333° to 413°K (table 9-8). Table 9-9 summarizes the values for each constituent at three temperatures. The value for holocellulose (avg. 0.3529) was nearly identical to that for alpha-cellulose (avg. 0.3526). The specific heat of lignin was somewhat less (avg. 0.3477), and that for extractives was substantially greater (avg. 0.4770). No comparable data are published for chemical constituents derived from hardwoods.

Specific heat of wood.—For ovendry whole wood representative of spruce pine trees (*Pinus glabra* Walt.) throughout their major commercial range, Koch (1969) determined the specific heat in the interval 60° to 140°C.

Specific heat = 0.2651 + 0.001004 (temperature in degrees C) (9-8)

This equation accounted for 95.4 percent of the observed variation with a standard error of estimate of 0.0072. Dunlap (1912) and Volbehr[6] have shown that, for wood species in general, the relationship between specific heat and temperature is also linear in the range 0° to 100°C (fig. 9-15).

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[6] Volbehr, B. 1896. Swelling of wood fibers. Unpublished doctoral thesis. Kiel.

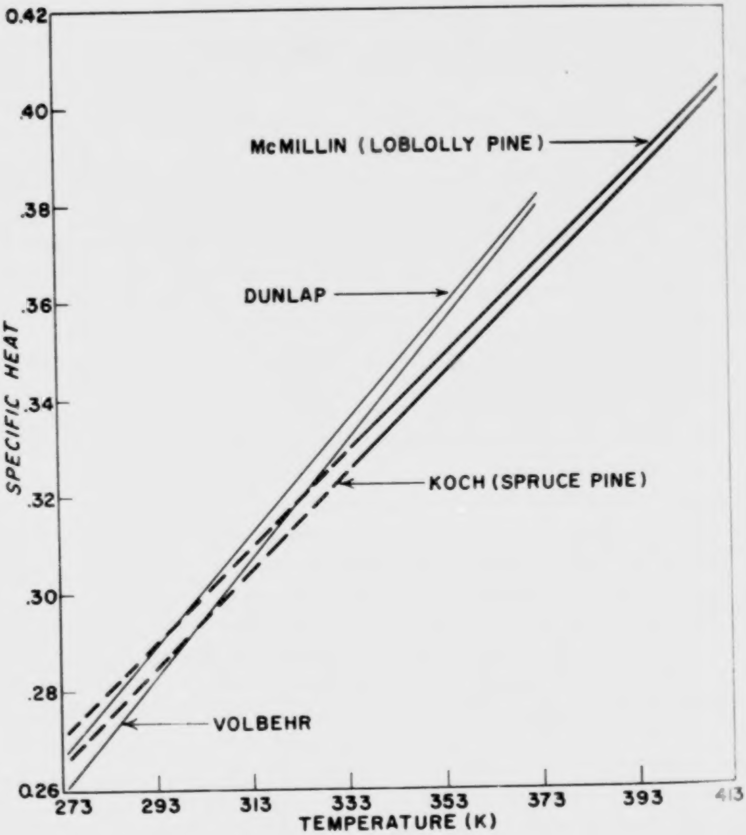

Figure 9-15.—Relationship of temperature (degrees Kelvin) to specific heat of ovendry wood as reported by Dunlap, Volbehr, Koch, and McMillin. (Drawing after McMillin 1969.)

McMillin (1969) determined the specific heat of ovendry loblolly pine wood in the range 333° to 413°K.

$$\text{Specific heat} = 0.0115321 + 0.009497\ (\text{temperature, degrees K}) \qquad (9\text{-}9)$$

The Wood Handbook (U.S. Forest Products Laboratory 1974) gives specific heat of dry wood as a function of temperature in °F (t), as follows:

$$\text{Specific heat} = 0.25 + 0.0006t \qquad (9\text{-}10)$$

TABLE 9-8.—*Regression equations of specific heat on temperature for chemical constituents of loblolly pine wood*[1,2] (data from McMillin 1970)

Constituent	Equation	Standard error of estimate	r^2
Holocellulose	$C_p = -0.01724 + 0.00099\ (K)$	0.0124	0.880
Alpha-cellulose	$C_p = -0.01708 + 0.00099\ (K)$	.0136	.858
Lignin	$C_p = 0.06133 + 0.00077\ (K)$	.0134	.791
Extractives	$C_p = 0.06945 + 0.00109\ (K)$	.0149	.890

[1] C_p = specific heat; K = temperature of observation in degrees Kelvin.
[2] Applicable within range of input data, i.e., 333° to 413°K.

TABLE 9-9.—*Specific heat of chemical constituents of loblolly pine wood*[1] (data from McMillin 1970)

Temperature of observation (°K)	Holocellulose	Alpha-cellulose	Lignin	Extractives
	Specific heat			
333	0.3110	0.3107	0.3165	0.4292
373	.3573	.3572	.3486	.4853
413	.3904	.3900	.3780	.5166
Mean	.3529	.3526	.3477	.4770

[1] Each numerical value is the average of 10 within-sample observations.

When wood contains water, the specific heat is increased because the specific heat of water is greater than that of dry wood. The apparent specific heat of moist wood, however, is larger than would be expected from a simple sum of the separate effects of wood and water (Hearman and Burcham 1955). The additional apparent specific heat is due to thermal energy absorbed by the wood-water bonds; as the temperature increases the apparent specific heat increases because the energy of absorption of wood increases with temperature.

The Wood Handbook (U.S. Forest Products Laboratory 1974) gives the specific heat of moist wood as follows:

$$\text{Specific heat} = \frac{M + C_o}{1 + M} + A \qquad (9\text{-}11)$$

where M is the fractional moisture content of the wood, C_O is the specific heat of dry wood, and A is the additional specific heat due to the wood-water bond energy. A increases with increasing temperature. For wood at 10 percent moisture content, A ranges from about 0.02 at 85°F to about 0.04 at 140°F. A ranges from about 0.04 at 85°F to about 0.09 at 140°F for wood at 30 percent moisture content.

HEAT TRANSMISSIVITY

Heat flow in wood is governed by the laws of diffusion. Two conditions of diffusion are of interest. The first, termed **steady state,** requires constant but different temperatures on each side of a wood product. In the second, called **unsteady state,** wood is either warming or cooling in response to changing temperatures. Under steady-state conditions, the temperature gradient across a wood slab is essentially linear and the heat flow is proportional to its **thermal conductivity.**

For determination of temperature gradients in the unsteady state, when wood is either warming or cooling, **thermal diffusivity** must be known. Thermal diffusivity is a measure of how quickly a material can absorb heat from its surroundings and change temperature; it is the ratio of thermal conductivity to the product of density and specific heat. For an extended discussion of the literature on these two properties of wood, the reader is referred to Wangaard (1969) or to a summary of this work found in Agriculture Handbook 420 (Koch 1972, p. 369-378).

The following brief discussion of thermal conductivity and diffusivity is taken from the Wood Handbook (U.S. Forest Products Laboratory 1974), with some additions from recent literature specific to species under study.

Thermal conductivity of solid wood.—The thermal conductivity of common structural woods is much less than that of metals, glass, or concrete products with which wood is often mated in construction. For example, southern red oak flooring (with specific gravity of 0.61 and moisture content in use of about 8-percent) has a conductivity of about 1.1 British thermal units per inch of thickness per hour, per square foot per degree Fahrenheit (Btu, in/hr, sq ft, deg F) compared with 1,390 for aluminum, 320 for steel, 8 for concrete, five for glass, and three for plaster. Mineral wool insulation has a thermal conductivity of 0.3, or about a quarter that of oak flooring.

Venkateswaran (1974) found that thermal conductivity of a variety of hardwoods and softwoods is positively correlated with their lignin content and shows close linear correlation with their dielectric constant; MacLean (1941) also attributed some variations in thermal conductivity to chemical composition, and to a positive correlation with extractive content. Wangaard (1943) noted that transverse thermal conductivity in Douglas-fir was positively correlated with fibril angle in the S_2 layer of tracheid walls; differences in thermal conductivity attributable of fibril angle were as much as 15 percent. He also found that the ratio of longitudinal to transverse thermal conductivity was inversely related to fibril angle; the ratio decreased as fibril angle increased.

More easily measured wood properties that are primary determinants of thermal conductivity include grain direction, moisture content, specific gravity, and structural irregularities such as checks and knots.

Thermal conductivity is nearly the same in radial and tangential directions in wood, but 2.0 to 2.8 times greater parallel to the grain than in either radial or tangential direction. It increases as the specific gravity or moisture content increases.

Up to approximately 40-percent moisture content, the following empirical equation (and fig. 9-16) relates thermal conductivity, k, measured perpendicular to the grain (Btu, in/hr, sq ft, deg F) to moisture content, M, (percent of dry weight) and specific gravity, S, (basis of current moisture content and weight):[7]

$$k = S(1.39 + 0.028M) + 0.165 \qquad (9\text{-}12)$$

For wood at a moisture content of 40 percent or greater, the following equation has been applied:

$$k = S(1.39 + 0.038M) + 0.165 \qquad (9\text{-}13)$$

These equations were derived by averaging the results of studies on a variety of species. Thermal conductivity of individual wood specimens will vary from these predicted values according to the previously mentioned significant factors not included in the equations.

Shrinkage from green to any moisture content can be derived from equations 8-4 and 8-5 with data from tables 8-4 and 8-10.

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[7] If S cannot be directly measured from current volume and ovendry weight, it can be calculated, as follows:

$$S = \frac{\text{specific gravity on the basis of ovendry weight and green volume}}{1 - \text{volumetric shrinkage, green to current, decimal fraction}}$$

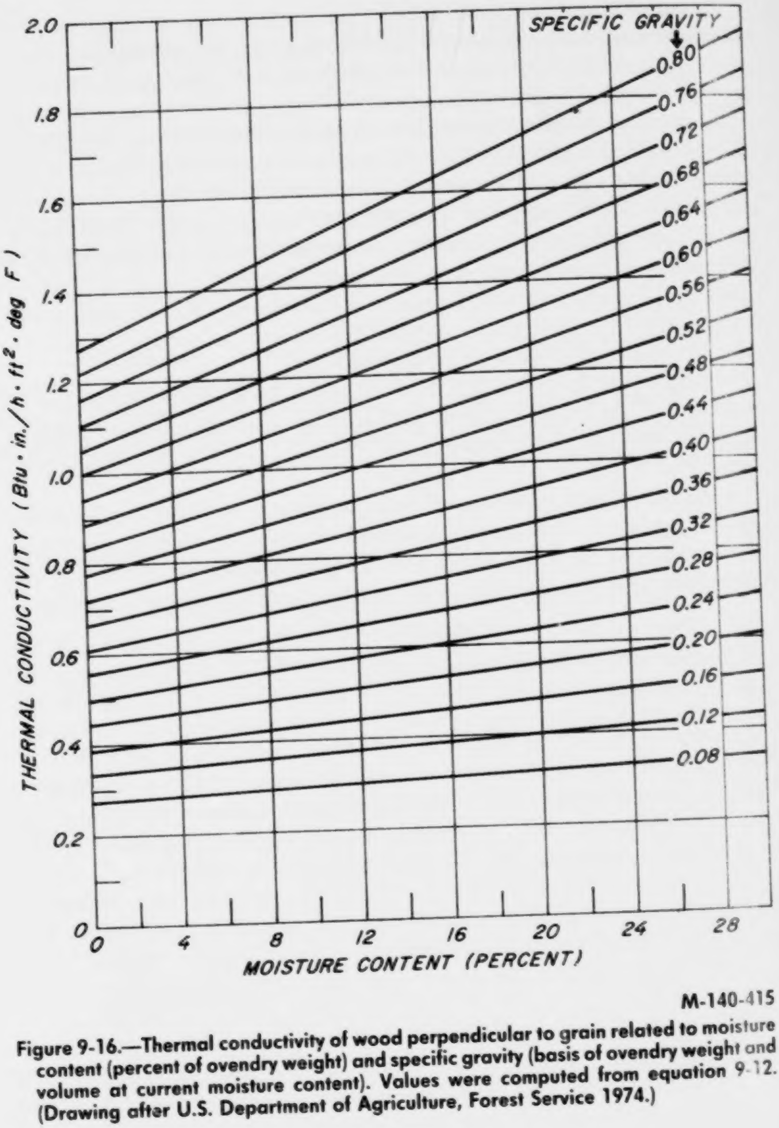

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Figure 9-16.—Thermal conductivity of wood perpendicular to grain related to moisture content (percent of ovendry weight) and specific gravity (basis of ovendry weight and volume at current moisture content). Values were computed from equation 9-12. (Drawing after U.S. Department of Agriculture, Forest Service 1974.)

Thermal conductivity of reconstituted wood.—Because fiberboards and particleboards (including flakeboards) will likely play a significant role in utilization of hardwoods on southern pine sites, some knowledge of their thermal conductivity is useful. At comparable densities, and moisture contents, solid wood has the highest thermal conductivity and fiberboard least; particleboards and flakeboards are intermediate (figs. 9-16, 9-17, and 9-18). For example, ovendry panels of 0.6 specific gravity (basis of ovendry weight and volume) evaluated at 75°F have design values for thermal conductivities about as follows:

Product	Thermal conductivity, k
	Btu, in/hr, sq ft, °F
Solid wood	1.00
Particleboard	.72
Fiberboard	.57

In figures 9-17 and 9-18, the dashed lines are intended to be used for design purposes in estimating thermal conductivity where insulation is desired. In situations where heat dissipation is desired, the lower curve would probably provide the more conservative estimate (Lewis 1967).

Inclusion of bark from western softwood species has been shown to reduce thermal conductivity in particleboards (Place and Maloney 1975). Schneider and Engelhardt (1977) found that platen-pressed particleboard made from beech (*Fagus* sp.) bark had about 30 percent less thermal conductivity parallel to the board plane than wood; perpendicular to the board plane, however, the bark board had 6-percent greater thermal conductivity than that of wood particleboard. Data specific to boards of bark from pine-site hardwoods are not available.

Readers wishing to further study the thermal conductivity of reconstituted wood products will find the following additional references useful:

Author	Subject
Kollmann and Malmquist (1956)	Über die Warmeleitzahl von Holz and Holzwerkstoffen.
Ratcliffe (1964)	A review of thermal conductivity data.
Teesdale (1958)	Thermal insulation made of wood-base materials—its application and use in houses.
Wangaard (1969)	Heat transmissivity of southern pine wood, plywood, fiberboard, and particleboard.
Ward and Skaar (1963)	Specific heat and conductivity of particleboard as functions of temperature.

Thermal diffusivity.—Thermal diffusivity is a function of conductivity, specific heat, and density, as follows:

$$h^2 = k/cd \qquad (9\text{-}14)$$

where, to illustrate appropriate units;

h^2 = thermal diffusivity, in ^{2}/sec
k = thermal conductivity, Btu, in/sec, sq in, deg F
d = density, pounds per cu in
c = heat capacity, Btu/lb, deg F

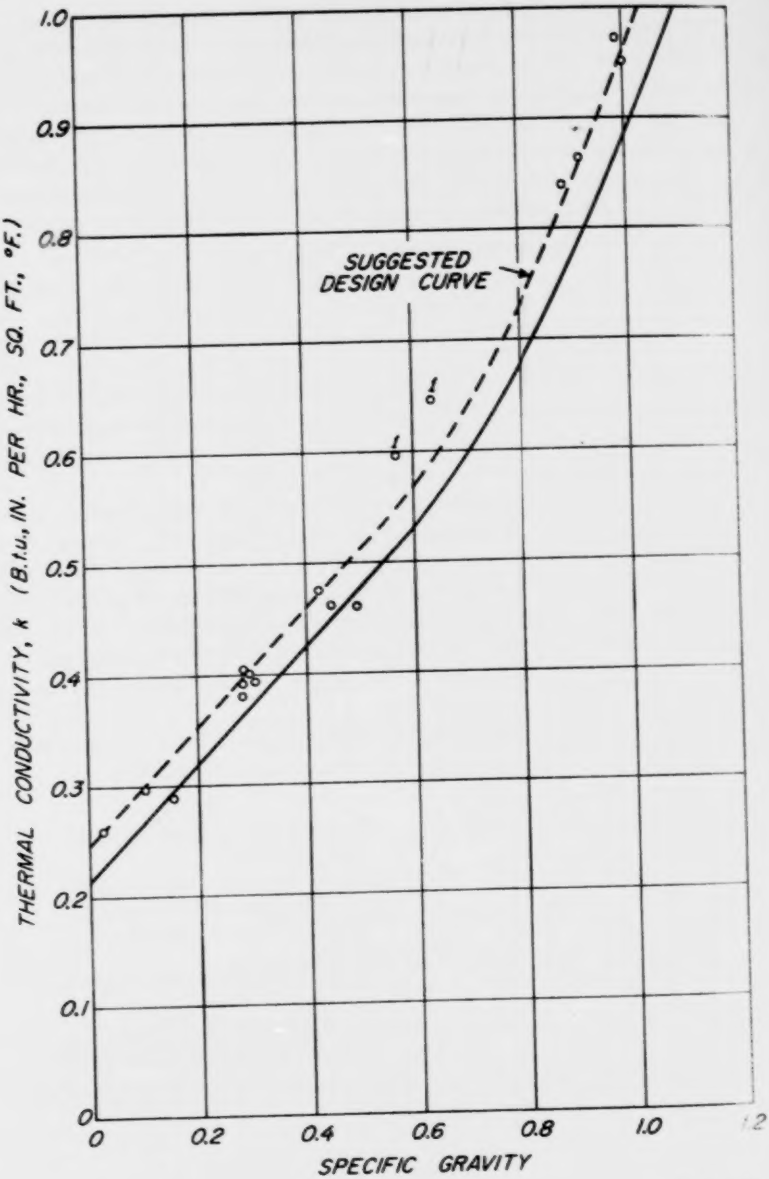

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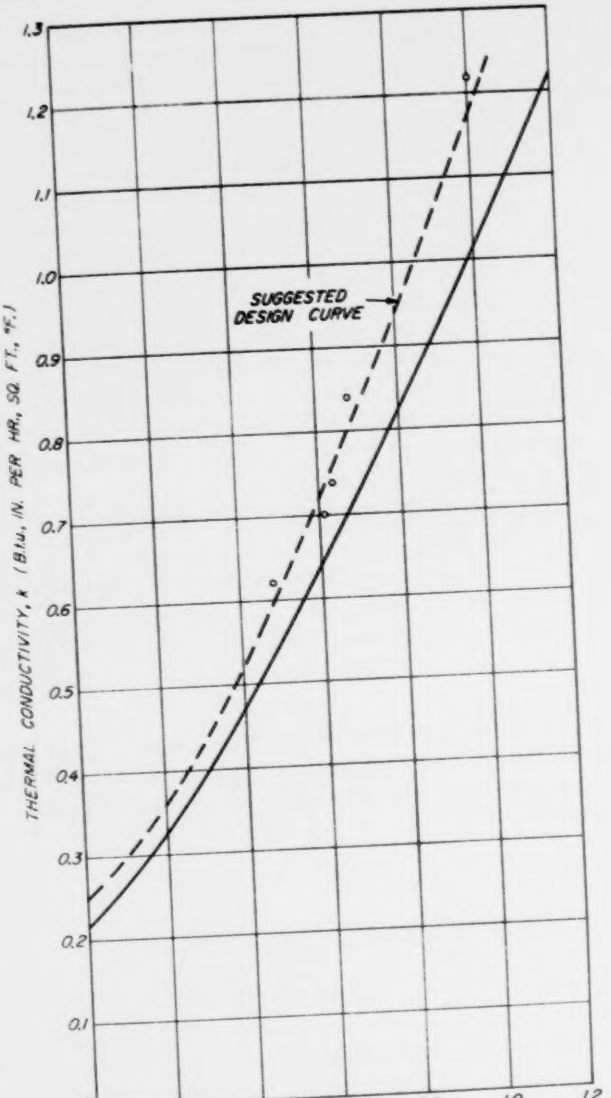
Figure 9-17.—Relationship of thermal conductivity to specific gravity (basis of ovend weight and volume) for typical building fiberboards evaluated when ovendry. The tw test points marked with the numeral 1 were siding products with high percentages thermoplastic additives. (Drawing after Lewis 1967.)



M-132-876

Figure 9-18.—Relationship of thermal conductivity to specific gravity (basis of ovendry weight and volume) for typical commercial particleboards evaluated when ovendry. (Drawing after Lewis 1967.)

Because of the low thermal conductivity and moderate density and specific heat of wood, the thermal diffusivity of solid wood is much less than that of other structural materials such as metals, brick, and stone. A typical value for wood is 0.00025 inch^2 per second compared to 0.02 inch^2 per second for steel, and 0.001 inch^2 per second for mineral wool. For this reason wood does not feel extremely hot or cold to the touch as do some other materials.

Few investigators have measured the diffusivity of wood directly. Since diffusivity is defined as the ratio of conductivity to the product of specific heat and density, conclusions regarding its variation with temperature and density often are based on calculating the effect of these variables on specific heat and conductivity (for example, see Koch 1972, p. 377-378).

All investigations illustrate that diffusivity is slightly and inversely influenced by both specific gravity and moisture content. The diffusivity increases approximately 0.0001 inch^2 per second over a range of decreasing specific gravity from 0.65 to 0.50. Calculations suggest that diffusivity increases by about 0.00004 inch^2 per second as the moisture content is reduced from 12 to 0 percent (U.S. Department of Agriculture, Forest Service 1974).

Some computed values of thermal diffusivity for reconstituted wood products follow (Koch 1972, p. 378):

Product	Specific gravity	Thermal diffusivity
		In^2/sec
Fiberboard	0.20	0.000322
Hardboard	1.00	.000177
Particleboard	.60	.000221

Readers desiring additional review of the literature should find Steinhagen's (1977) summarization of data from Kanter (1957) and Chudinov (1968) useful; these data allow estimation of specific heat, thermal conductivity, and thermal diffusivity at temperatures from −40° to +100°C and at moisture contents up to 130 percent.

THERMAL EXPANSION AND CONTRACTION

Ovendry wood.—Dry southern hardwoods, like most woods and other solids, expand when heated and contract when cooled. The coefficient of linear expansion, defined as the increase in length per unit length for a temperature rise of 1°C, differs in the three structural directions of wood. Over the range from −50 to +50°C, thermal expansion of ovendry woods in the three structural directions is essentially linear (Weatherwax and Stamm 1947; Kubler et al. 1973).

Data specific to southern hardwoods are limited to northern red oak and yellow-poplar (table 9-10). These data suggest little correlation between thermal expansion and specific gravity, except possibly in the longitudinal direction.

TABLE 9-10.—*Coefficients of linear thermal expansion per °C in dry stemwood of northern red oak and yellow-poplar*

Statistic	Northern red oak	Yellow-poplar	Yellow-poplar
Temperature range observed (°C)	0 to +50	0 to +50	−50 to +50
Specific gravity (based on ovendry weight and volume)	0.62	0.43	0.43
Coefficient of tangential thermal expansion times 10^6	32	31.4	29.7
Coefficient of radial thermal expansion times 10^6	26	27.2	27.8
Coefficient of longitudinal thermal expansion times 10^6	9	3.6	3.2
Data source	Kubler et al. (1973)	Weatherwax and Stamm (1947)	

Stamm (1964, p. 289) reported that coefficients of linear expansion of dry wood in the fiber direction are virtually independent of species and specific gravity, but that in radial and tangential directions the coefficients of thermal expansion are positively correlated with specific gravity. He found different relationships for low-density and high-density species. Among softer hardwoods such as yellow-poplar and eastern cottonwood (*Populus deltoides* Bartr.), he reported the following relationships for dry wood:

$$a_r = (56\ G)\ (10^{-6}) \tag{9-15}$$

$$a_t = (81\ G)\ (10^{-6}) \tag{9-16}$$

For dry denser hardwoods such as yellow birch (*Betula alleghaniensis* Britton) and sugar maple (*Acer saccharum* Marsh.), he found the following relationships:

$$a_r = (45\ G)\ (10^{-6}) \tag{9-17}$$

$$a_t = (58\ G)\ (10^{-6}) \tag{9-18}$$

where:

a_r is radial coefficient of linear expansion per °C.
a_t is tangential coefficient of linear expansion per °C.
G is specific gravity (basis of ovendry weight and volume).

Researchers caution that there is substantial variation in these coefficients among samples within a species (Kubler et al. 1973).

Moist wood.—Kubler et al. (1973) measured linear expansion in moist northern red oak and yellow birch (table 9-11). Linear thermal expansion, measured on cylindrical specimens sealed at constant moisture content, generally increased with the amount of bound water. This is explained as due to the low stiffness of moist wood. Near fiber saturation and above, however, at temperatures above 0°C, shrinkage from internal drying, due to water migrating out of saturated cell walls obscured true thermal expansion. Observations of tangential expansion are summarized in figure 9-19.

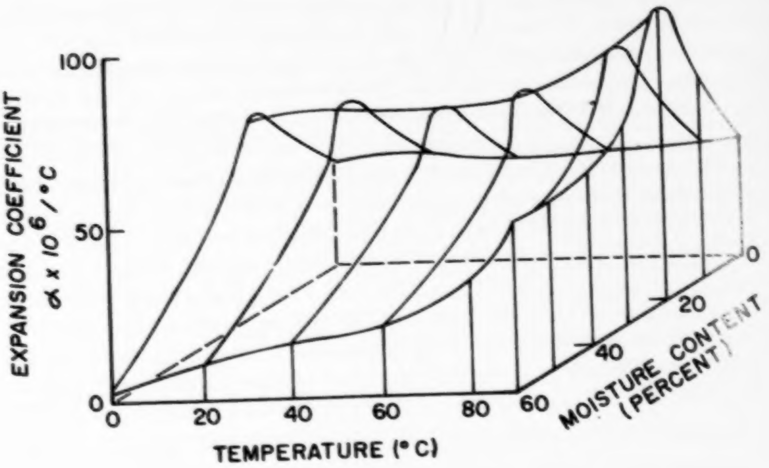


Figure 9-19.—Average coefficients of tangential thermal expansion for northern red oak, yellow birch, and Douglas-fir during heating from 0°C (not frozen) to 90°C. (Drawing adapted from Kubler et al. 1973.)

TABLE 9-11.—*Average coefficients of thermal expansion for moist and dry wood between 0° and 50°C* (data from Kubler et al. 1973)

Direction and moisture content (percent of dry weight)	Northern red oak[1]	Yellow birch[2]	Yellow birch plywood[3]
	Coefficient X 10^6/°C		
Tangential			
0	32	28	—
12	70	37	—
>60	0	12	—
Radial			
0	26	26	—
12	44	41	—
>60	0	4	—
Longitudinal			
0	9	9	5.5
12	8	10	9.5
>60	0.3	9.6	4.5

[1] Specific gravity 0.62 based on ovendry volume and weight.
[2] Specific gravity 0.58 based on ovendry volume and weight.
[3] 11 plys each 2 mm thick bonded with phenolic resin.

During cooling at freezing temperatures, tangential shrinkage due to moisture diffusing out of cell walls and condensing as ice crystals in cell cavities supplemented true thermal contraction. During heating of moist wood from − 10°C to 0°C, expansion coefficients were about 0.0002/°C, substantially above those of dry wood, which remained at about 0.00003/°C, through this temperature range.

Excessive tangential shrinkage below 0°C accounts for the frost cracks prevalent in a few species of living trees. Fergus (1955) observed that frost cracks in scarlet oak and white oak in central Pennsylvania were most frequent in larger trees. They ranged in length up to 21 feet, averaged 2.8 feet, occurred at various heights in the bole, and in most cases were healed; 23 percent of those on scarlet oaks showed extensive callus growth called **frost ridges.**

Veneer logs, bolts, and flitches with boxed heart of dense species such as oak frequently crack when softened in steam or hot water (Fleischer 1951).

Kubler (1977) attributes these heart checks mainly to hygrothermal tangential expansion and radial contraction which occur in moist wood when heated for the first time, although transverse growth stresses and relief of longitudinal growth stresses by crosscutting also contribute. Relief of longitudinal stresses concentrate such cracks at log ends; thus heated short bolts have more checks than heated long stems. Cracking increases with increasing wood temperature and with time of exposure to high temperatures; timbers should, therefore, not be heated more than necessary. Different heating rates have no influence on cracking. It also makes no difference if the heat flows into the wood through the bark or from the pith outward. Heating insulation of log ends is useless, whereas, central holes bored into log ends can be expected to reduce cracking, but the holes have to be quite large to be effective (Kubler 1977).

Reconstituted wood.—Kubler et al. (1973) found that 11-ply yellow-birch plywood expands no more than solid yellow-birch in the fiber direction (fig. 9-20 top). As with solid wood, expansion peaked within the hygroscopic moisture range (0 to about 30-percent), though the peak appeared at a lower moisture content (fig. 9-20 bottom). Below 0°C longitudinal coefficients for wet wood varied widely.

The coefficient of thermal expansion of plywood in the thickness direction is about the same as that of parallel-laminated material (Weatherwax and Stamm 1947).

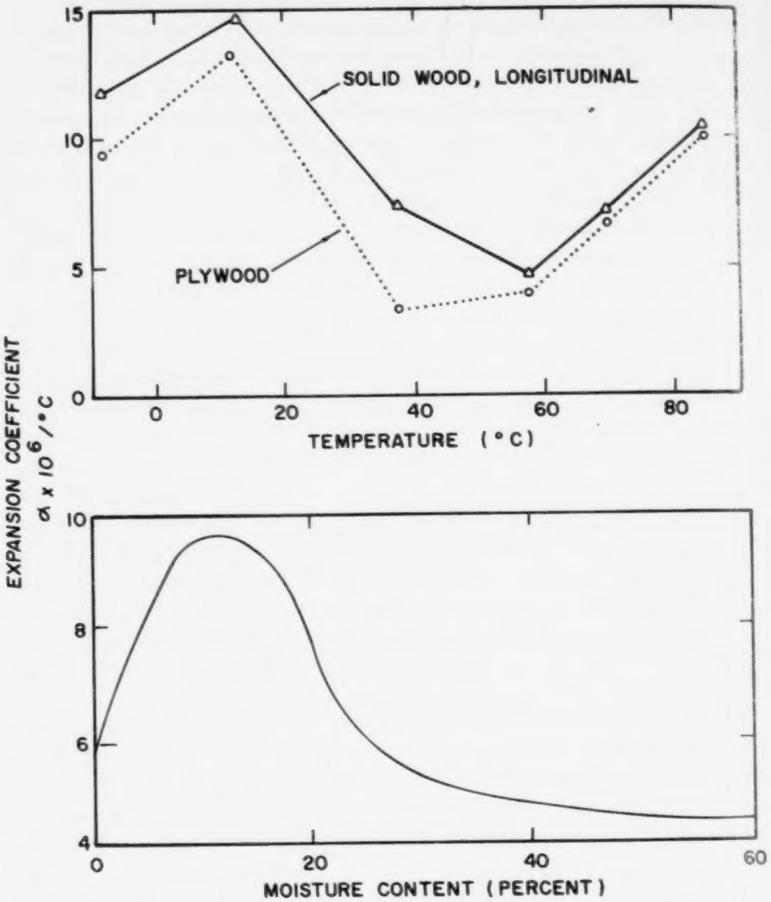


Figure 9-20.—(Top) Average coefficients of linear thermal expansion in the hygroscopic moisture range for solid yellow birch in the longitudinal direction and for 11-ply yellow birch plywood. (Bottom) Average linear thermal expansion of yellow birch plywood between −16° and 95°C, exclusive of wet plywood below 0°C. (Drawing after Kubler et al. 1973.)

High-pressure wood fiber laminates are much used as decorative faces laminated to particleboard cores, to which wood fiber backing sheets are laminated on the side concealed in use. Sometimes aluminum or steel are part of the composite sandwich. To maintain flatness with change of temperature, the various layers should have coefficients of thermal expansion that are about equal. Heebink and Haskell (1962) found that the coefficients of thermal expansion of dry particleboard core are nearly the same for both linear directions in the board (length and width) and are about intermediate between decorative laminates and backing sheets (both wood fiber products). For decorative laminates and backing sheets, the values in the across-the-machine direction were about twice those in the machine direction (along which the fibers tend to be aligned). The coefficients of thermal expansion of the decorative laminates tested were greater than those of the backing sheets (fig. 9-21).

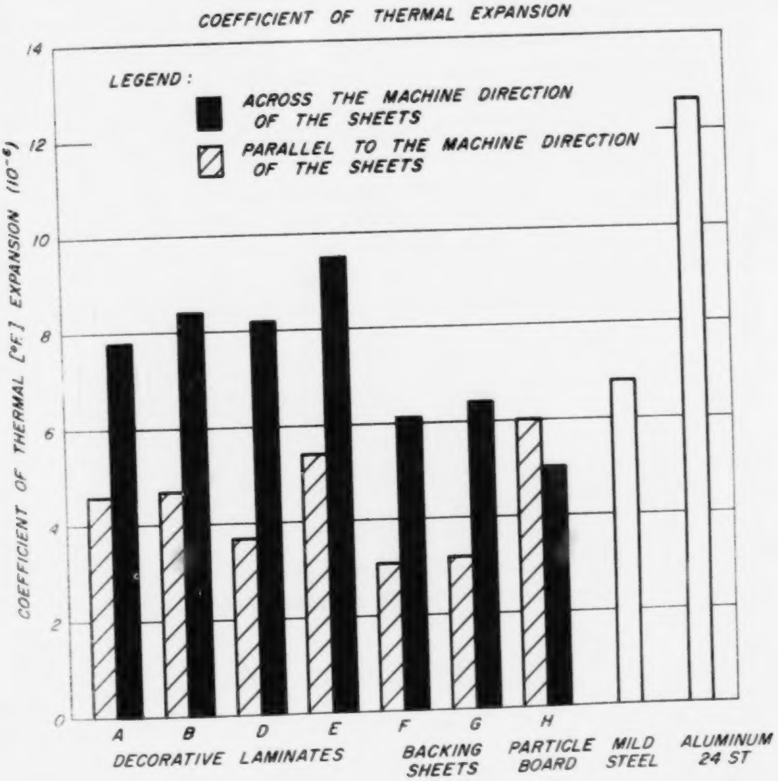


Figure 9-21.—Coefficient of thermal expansion of wood fiber plastic laminates and particleboard compared with mild steel and aluminum. (Drawing after Heebink and Haskell 1962.)

Expansion coefficients of particleboard across-the-machine were lower than for any laminates or backings, but parallel-to-the-machine they were higher than any of them. When large, these differences can cause cupping with temperature changes.

HEAT OF COMBUSTION

Heat of combustion is the quantity of heat evolved by the complete combustion of a unit mass of substance. As used in this text, it is the total amount of heat obtainable from ovendry material when burned in an enclosure of constant volume, allowing no deductions for heat losses. The available heat obtained by burning in open systems is considerably less, as heat is permitted to escape in the form of steam and other gases.

In oxygen-bomb calorimetry, a weighed sample is burned in an oxygen-filled metal "bomb" submerged in a measured quantity of water, all held within an insulated chamber. The number of heat units liberated by explosive combustion of the sample may be calculated from the rise in water temperature, with corrections for the heat of formation of nitric acid from atmospheric nitrogen present and heat of combustion of the fuse wire. The values obtained (**higher heating values**) provide a basis for comparison of fuels.

Heat of combustion of woody material varies considerably with chemical content. Resin, tannins, lignin, terpenes, and waxes have high heat content; carbohydrates are relatively low in heat. Murphey and Masters (1978) found that components of northern red oak wood from Pennsylvania had heats of combustion as follows:

Component	Heat of combustion (higher heating value)
	Btu/ovendry lb
Cellulose	7,320
Hemicellulose	7,165
Lignin	9,105
Extractive-free ovendry wood	8,575

Wood and bark of the southern pines have heats of combustion (higher heating value) of about 8,600 and 8,900 Btu/lb, respectively (Koch 1972, p. 379 and 380).

Heats of combustion of components of 6-in. hardwoods of 23 species sampled from among southern pines average somewhat lower, as follows:

Component	Reference table	Heat of combustion (higher heating value)
		Btu/ovendry lb
Wood		
Stemwood	9-12	7,827
Branchwood	9-12	7,784
Wood from stump-root system	14-12	8,333
Bark		
Stembark	9-12	7,593
Branchbark	9-12	7,632
Bark from stump-root system	14-12	7,657

Foliage heat of combustion for pine-site hardwoods probably averages slightly more than 8,000 Btu per ovendry pound (sec. 15-4).

TABLE 9-12.—*Heat of combustion of stems and branches of 6-inch trees of 22 hardwood species growing on southern pine sites*[1,2] (Data from Manwiller[3])

Species	Stem-wood[4]	Stem-bark[4]	Branch-wood[5]	Branch-bark[5]
	Btu/ovendry pound			
Ash, green	7,695	7,472	7,727	7,606
Ash, white	8,033	7,695	8,013	7,816
Elm, American	7,770	6,840	7,857	6,904
Elm, winged	7,917	7,019	7,869	6,889
Hackberry[6]	7,882	7,147	7,867	7,141
Hickory, sp.	8,183	7,586	7,931	7,259
Maple, red	7,846	7,595	7,829	7,384
Oak, black	7,680	7,642	7,692	7,847
Oak, blackjack	7,739	7,766	7,739	7,907
Oak, cherrybark	7,848	7,582	7,737	7,655
Oak, laurel	7,828	7,897	7,653	7,806
Oak, northern red	7,791	7,879	7,776	7,926
Oak, post	7,889	7,191	7,845	7,728
Oak, scarlet	7,798	8,041	7,673	7,894
Oak, Shumard	7,789	7,970	7,745	7,913
Oak, southern red	7,919	7,983	7,839	7,798
Oak, water	7,876	7,930	7,833	7,918
Oak, white	7,676	7,328	7,507	7,574
Sweetbay	7,736	7,822	7,802	7,886
Sweetgum	7,667	7,200	7,690	7,214
Tupelo, black	7,867	7,788	7,814	8,176
Yellow-poplar	7,774	7,696	7,811	7,666
Average	7,827	7,593	7,784	7,632

---

[1] Higher heating value determined in an oxygen-bomb calorimeter.

[2] Each value is the average for 10 trees. See tables 3-1 and 16-3 for description of trees sampled.

[3] Manwiller, F.G. Unpublished data in Study File FS-SO-3201-1.44. U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Pineville, La.

[4] From a point 6 inches above ground level to the point where the central stem could no longer be distinguished, or to a 0.5 inch minimum diameter outside bark.

[5] From the point of juncture with central stem extending out to a branch diameter of 0.5 inch outside bark.

[6] Mostly sugarberry.

The range in heats of combustion among stemwoods of 6-inch pine-site hardwoods of 22 species is not great—7,667 Btu/lb in sweetgum to 8,183 Btu/lb in hickory (table 9-12). In stembark of these trees the range is somewhat greater—i.e., from 6,840 Btu/lb in American elm to 8,041 in scarlet oak.

Wood from the stump-root system has highest heat of combustion, probably because of high lignin and extractives content. Hackberry rootwood has highest heat of combustion (9,038 Btu/lb); post oak (8,879), yellow-poplar (8,735), and water oak (8,728) are next highest. Northern red oak rootwood, at 7,972 Btu/lb, has lowest heat of combustion. Rootwoods of the other 17 species have heats of combustion from 8,091 to 8,453 Btu/lb (table 14-12).

While hackberry rootwood from 6-in trees has the highest heat of combustion, its rootbark has lowest (6,997 Btu/lb), probably because of its 16.42-percent ash content (table 14-10). Southern red oak rootbark, with only 7.87 percent ash content, has highest heat of combustion (8,273 Btu/lb). Rootbark of the other species has heats of combustion from 7,173 to 8,021 Btu/lb (table 14-12).

For data on heat of combustion of stembark from larger trees see tables 13-44 and 13-45.

Wood and bark residues.—Table 13-46 gives data on heats of combustion of fresh and piled sawmill residues of wood and bark from southern hardwoods at six Louisiana sawmills, along with moisture contents of such residue.

Figure 11-23 relates heat of combustion in wood-bark residue piles to time in storage, and indicates that heat content per ovendry pound increases during 4 months of storage. Moisture content of hardwood bark in residue piles sampled in Virginia did not decrease in moisture content during 5 months of storage; a mixture of hardwood and southern pine sawdust did decrease slightly in moisture content during this period, however (fig. 11-22). See also figures 20-18AB and related discussion.

Moisture content and available heat.—For a discussion of heat recoverable in a boiler as a function of moisture content, and for an example of a typical computation of available heat, see paragraph **Moisture content and available heat** under subsection HEAT OF COMBUSTION in section 13-6, pp. 1225-1226. See also page 847.

Moisture contents of various fuels are given in the following tables, figures, and sections:

Fuel	Table, figure, or section
Stemwood and stembark	Tables 8-1, 8-1A, 8-2
Branchwood and branchbark	Tables 8-1A, 8-2, 14-7
Rootwood and rootbark	Table 14-7
Foliage	Table 14-7, section 15-4, figures 15-17 through 15-19
Bark	Section 13-4, figures 13-67 through 13-69
Residues	Table 13-46, section 13-4, figure 11-22

For a graph designed as a tool for comparing the cost of heat or steam produced from wood-based and fossil fuels, see figures 26-5 and 26-6.

Charcoal.—Substantial volumes of eastern hardwoods are converted to charcoal. In one determination of the heat of combustion (higher heating value) of charcoal briquets, the average was 12,335, with range from 11,225 to 12,740 Btu/ovendry lb. Pure carbon has a heat of combustion of 14,100 Btu/lb. Probably the lower values observed for the briquets are attributable to their high ash content and to the low heat value of the starch binder used in their manufacture.

9-4 FRICTIONAL PROPERTIES

The coefficient of friction of wood against steel affects the holding power of mechanical fasteners, the configuration of chips and surfaces produced by machining operations, and the feed power required to slide or feed wood through processing equipment.

The **coefficient of friction** between two surfaces (μ) is defined as the ratio of horizontal force required to initiate motion between them to the vertical force holding them in contact (**static friction**), or the ratio to maintain constant velocity between the two (**dynamic friction**). The coefficient of static friction is always equal to, or greater than, the coefficient of dynamic friction.

From experiments with **southern pine** using the apparatus and specimen configuration shown in figures 19-22 and 19-23, Lemoine et al. (1970) found that dynamic friction coefficient on smooth steel was maximum for unextracted transverse surfaces of high moisture content pulled parallel to the growth rings (0.263). It was minimum for extractive-free transverse surfaces of high moisture content pulled perpendicular to the rings (0.165). McMillin et al. (1970a), using the same apparatus, found that the dynamic friction coefficient of southern pine was negatively correlated with temperatures of the steel in the range from 75 to 225°F; the friction coefficients ranged from 0.10 to 0.25. McMillin et al. (1970b) also found that application of water, ethanol, or octanoic acid reduced the coefficient of friction between steel and saturated southern pine wood, but only octanoic acid reduced the coefficient with dry wood. Application of water doubled the coefficient of friction between dry southern pine and smooth steel.

In their experiments the horizontal force (F_h) required to slide a 1-square-inch surface subjected to a known vertical force component (F_V) was measured and the coefficient of dynamic friction (μ) calculated by the relationship:

$$\mu = F_h/F_v \qquad (9\text{-}19)$$

An Instron testing machine was used to maintain a constant sliding velocity of 2 inches per minute as well as to measure the horizontal force (fig. 9-22). A thin copper wire was attached to the specimen and to a 1-pound load cell mounted on the movable crossarm of the testing machine. Movement of the crossarm thus provided a constant sliding velocity, while the load cell simultaneously detected the horizontal force component. A 1-pound weight was placed on the upper surface of the cube and it, plus the weight of the sample, was considered the total vertical force component.

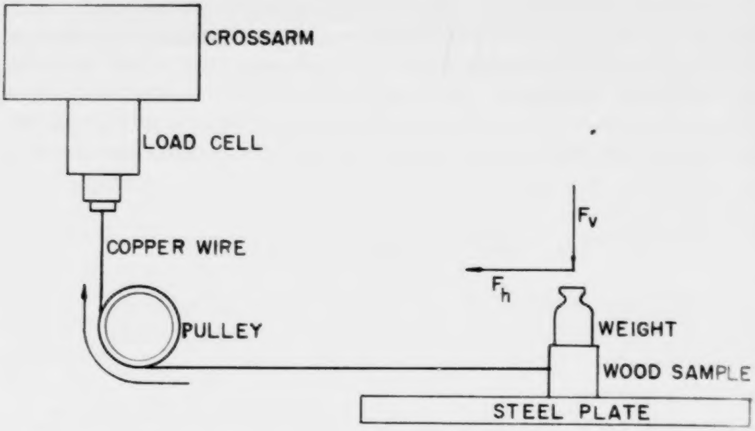

CROSSARM
LOAD CELL
COPPER WIRE
PULLEY
F_v
F_h
WEIGHT
WOOD SAMPLE
STEEL PLATE

Figure 9-22.—Experimental setup for determining coefficient of friction. (Drawing after Lemoine et al. 1970.)

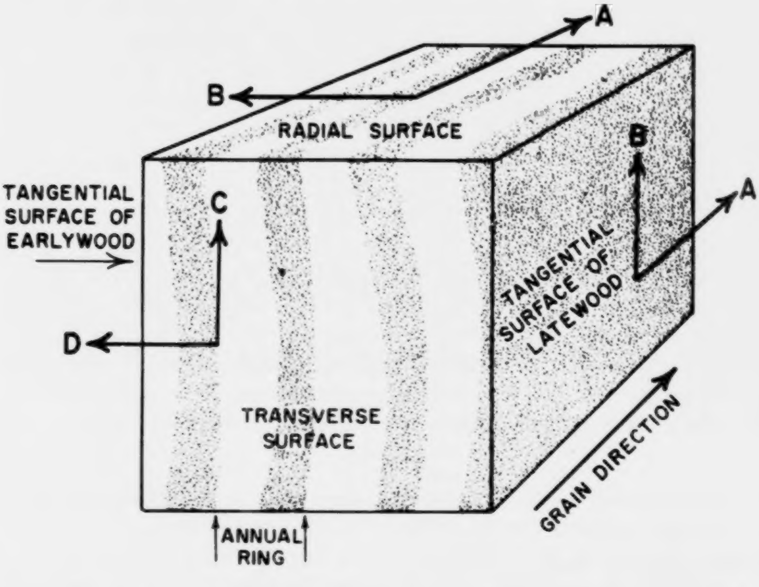

A
B
RADIAL SURFACE
B
A
TANGENTIAL SURFACE OF EARLYWOOD
C
D
TANGENTIAL SURFACE OF LATEWOOD
TRANSVERSE SURFACE
GRAIN DIRECTION
ANNUAL RING

Figure 9-23.—Friction specimens. The letters A, B, C, and D refer to direction of slide in relation to grain orientation. Direction A is parallel to the wood grain, while direction B is perpendicular. Direction C is parallel to the growth rings, while direction D is perpendicular. (Drawing after Lemoine et al. 1970.)

An oil-hardened, tool steel plate was used as the stationary surface. Its surface roughness was 9 microinches root mean square (RMS)[9], and the specimens were pulled parallel to the grinding marks. Wood surfaces were sanded with 220-grit sandpaper. Prior to each force determination the steel plate was cleaned with petroleum ether and water, then thoroughly dried with lint-free paper tissue.

Published data specific to hardwoods grown on southern pine sites are limited to those obtained by Lemoine and Koch (1975) and Price and Manwiller.[10] In both of these hardwood studies, procedures were similar to those just described.

EFFECT OF SPECIES AND WOOD VARIABLES

Price and Manwiller[10] evaluated the dynamic coefficient of friction of breast-height stemwood, equilibrated to 13 percent moisture content, from ten 6-in trees of each of 22 species of pine-site hardwoods sampled from widely separated locations throughout that portion of each species range occurring in the 11 Southern States from Virginia to Arkansas and eastern Texas. Transverse, radial, and tangential surfaces were evaluated in motion parallel and perpendicular to growth rings (fig. 9-23).

Price and Manwiller found that coefficient of friction averages ranged from 0.097 to 0.127, while individual values ranged from 0.077 to 0.185; the grand mean for all values was 0.113 (table 9-13). For the 22 species evaluated, transverse surfaces pulled parallel to the growth rings had the lowest coefficient (0.106), and radial surfaces pulled perpendicular to the grain had the highest (0.117). Hickory, black tupelo, and ten of the eleven oaks tested had mean friction coefficients from 0.108 to 0.112; water oak and the other nine non-oaks had mean friction coefficients of 0.115 to 0.118.

Murase (1980) found that dynamic friction coefficient of dry wood on smooth steel increased with sliding distance, but friction coefficient of water saturated specimens under running water changed little. Friction coefficient of dry wood (1.5 to 19 percent moisture content) was approximately independent of sliding speed; for wet wood (29-63 percent moisture content), friction coefficient decreased rapidly with increasing sliding speed up to 5 m/sec, but was little diminished at higher speeds. Murase also found that the dynamic coefficient of friction decreased with increase in specific gravity of air-dry wood specimens.

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[9] For definition of RMS see Peters and Cumming (1970).

[10] Price, E. W., and F. G. Manwiller. 1982. Friction coefficient (on steel) of twenty-two hardwood species, as related to grain orientation. Final Report (Part II) FS-SO-3201-1.45, on file at the South. For. Exp. Stn., U.S. Dep. Agric., For. Serv., Pineville, La.

TABLE 9-13.—*Average friction coefficient for various surfaces of 22 hardwood species determined by sliding over a smooth steel surface*[1] (Price and Manwiller, text footnote[10]

Species[2]	μ[3] Transverse		μ[3] Radial		Transverse and radial		μ[3] Tangential		Tangential		μ[3] Species mean
	Perp[4]	Para[5]	Perp[4]	Para[5]	Sp Gr[6]	MC[7]	Perp[4]	Para[5]	Sp Gr[6]	MC[7]	
Ash, green	0.120	0.109	0.116	0.117	0.563	14.1	0.108	0.120	0.558	14.3	0.115
Ash, white	.117	.108	.120	.115	.603	13.7	.116	.117	.590	13.6	.115
Elm, American	.114	.110	.119	.113	.561	12.6	.119	.115	.561	12.7	.115
Elm, winged	.115	.110	.124	.116	.664	13.2	.117	.123	.672	13.4	.118
Hackberry	.118	.110	.118	.112	.527	13.6	.112	.119	.523	13.4	.115
Hickory, true	.113	.106	.112	.114	.699	13.8	.111	.110	.706	13.6	.111
Maple, red	.120	.111	.119	.116	.519	12.6	.116	.121	.524	12.4	.117
Oak, black	.109	.104	.117	.114	.654	12.6	.113	.117	.645	12.9	.112
Oak, blackjack	.104	.097	.114	.109	.693	12.3	.109	.116	.679	13.2	.108
Oak, cherrybark	.112	.107	.119	.110	.653	12.9	.113	.113	.647	13.0	.112
Oak, laurel	.109	.103	.111	.108	.600	12.9	.110	.110	.610	12.6	.108
Oak, northern red	.107	.105	.115	.110	.629	12.1	.112	.113	.628	12.4	.110
Oak, post	.106	.097	.114	.108	.749	13.2	.108	.112	.711	13.0	.108
Oak, scarlet	.109	.099	.115	.109	.631	12.5	.103	.114	.624	12.5	.108
Oak, Shumard	.109	.099	.116	.108	.639	12.5	.109	.115	.631	13.3	.110
Oak, southern red	.109	.105	.118	.111	.636	12.5	.114	.115	.640	12.1	.112

TABLE 9-13.—*Average friction coefficient for various surfaces of 22 hardwood species determined by sliding over a smooth steel surface*[1] (Price and Manwiller, text footnote[10])—Continued

Species[2]	μ[3] Transverse		μ[3] Radial		Transverse and radial		μ[3] Tangential		Tangential		μ[3] Species mean
	Perp[4]	Para[5]	Perp[4]	Para[5]	Sp Gr[6]	MC[7]	Perp[4]	Para[5]	Sp Gr[6]	MC[7]	
Oak, water	.116	.109	.127	.114	.609	12.3	.115	.125	.602	12.2	.118
Oak, white	.109	.105	.113	.106	.726	13.3	.109	.116	.705	13.4	.110
Sweetbay	.121	.115	.126	.116	.443	12.8	.113	.125	.446	12.9	.119
Sweetgum	.119	.110	.116	.111	.478	13.0	.110	.111	.480	13.0	.113
Tupelo, black	.115	.104	.115	.111	.557	12.7	.109	.108	.553	12.7	.110
Yellow-poplar	.115	.109	.114	.113	.436	12.6	.112	.117	.434	12.6	.114
Surface mean	.113	.106	.117	.112	—	—	.112	.116	—	—	.113

[1] Average of 10 trees/species.
[2] See tables 3-1 and 16-3 for tree descriptions.
[3] Dynamic coefficient of friction.
[4] Perpendicular to growth rings or grain direction.
[5] Parallel to growth rings or grain direction.
[6] Specific gravity (species mean) based on ovendry weight and volume at given moisture content.
[7] Percent moisture content (species mean), ovendry weight basis.

MATERIALS WITH HIGH FRICTION COEFFICIENTS

For some purposes, e.g., facing grips in tension testing machines, a very high coefficient of friction is required between substrate and dry wood. Lemoine and Koch (1975) provided some information on static and dynamic friction coefficients between red oak and a selection of such surfaces. Four materials were studied:

- A tool-steel plate with surface roughness of nine microinches RMS[9].
- 220-grit garnet sandpaper.
- Riehle testing machine "sand-coated" facings on steel tension grips.
- A sample of proprietary polyurethane, of 65-70 durometer hardness manufactured by Griffith Polymers, Portland, Ore.

The static coefficients on garnet paper, polyurethane, or Riehle jaw facings were 8 to 10 times those on smooth steel (table 9-14). Static friction coefficients for tangential oak surfaces were slightly higher than those on radial surfaces resting on polyurethane or Riehle jaw facings.

Dynamic coefficient was 6 to 8 times greater for garnet paper, polyurethane, and Riehle jaw facings than for smooth steel. Only on smooth steel was the static coefficient equal to the dynamic (so the ratio of static to dynamic was 1.0). With the other materials, static coefficient was 10 to 50 percent more than dynamic (table 9-14).

Murase (1977), in experiments with wood sliding on steel, found that the coefficient of friction was more-or-less independent of surface roughness of the wood, but increased with increased surface roughness of the steel.

TABLE 9-14.—*Parallel-to-grain friction coefficients for southern red oak of 10-percent moisture content (dry-weight basis) at 70°F on four substrates*
(Data from Lemoine and Koch 1975)

Statistic and wood surface	Smooth steel	220-grit garnet paper	Griffith polyurethane	Riehle jaw facing
	μ			
Static coefficient				
Radial	0.1	0.9	0.9	0.8
Tangential	.1	.9	1.0	.9
Dynamic coefficient				
Radial	.1	.7	.7	.6
Tangential	.1	.8	.7	.6
Ratio of static to dynamic coefficient				
Radial	1.0	1.3	1.3	1.3
Tangential	1.0	1.1	1.4	1.5

Workers applying shingles to roof sheathing need secure footing. Fortunately, commonly used shoe sole materials have high friction coefficients on wood-based panel products. The following data on structural flakeboard made of southern hardwoods and textured during pressing with a coarse screen pattern is abstracted from table 24-24:

Shoe sole material (smooth)	Dry flakeboard	Wet flakeboard
	----Static friction coefficient---	
Leather	0.50	0.91
Neoprene	.91	.54
Crepe composition	1.22	.94

See table 24-24 for data on southern pine plywood and these shoe-sole materials.

9-5 ACOUSTICAL PROPERTIES

The building industry is a major market for wood products; therefore, the most significant acoustical properties of wood are those related to architectural acoustics. For a brief treatment of this subject, the reader is referred to Koch (1972, p. 346-357).

To a limited degree, the vibrational properties of wood are also used in nondestructive testing to classify individual pieces of lumber according to strength.

NONDESTRUCTIVE TESTING

Velocity of stress (or sound) waves travelling longitudinally in wood is proportional to dynamic modulus of elasticity, which is correlated with static modulus of elasticity; both moduli are in turn correlated—but to a lesser degree—with modulus of rupture (Galligan and Courteau 1965; Marra et al. 1966; Koch and Woodson 1968).

The basic equation for determining modulus of elasticity in slender bars by this means is:

$$E_d = v^2 \frac{d}{g} \qquad (9\text{-}20)$$

where

E_d = dynamic modulus of elasticity, psi
v = velocity of stress wave propagation, inches per second
d = density, pounds per cubic inch based on weight and volume at time of test
g = acceleration due to gravity (386 inches per second per second)

Price[11] cut 1-in-square by 28-in-long specimens from stemwood of ten 6-in-dbh trees of 22 hardwood species (see tables 3-1 and 16-3 for tree descriptions), equilibrated them to about 9 percent moisture content, and determined their moduli of elasticity by two methods: velocity of stress (or sound) waves, and quasistatic loading. Longitudinal stress waves were excited by a solenoid-operated hammer striking the specimen end. Quasistatic loading was accomplished by deflecting the specimens with a center-point load over a 24-in span following ASTM 143-52.

The longitudinal velocity of sound in these dry hardwoods averaged intermediate to that in copper and aluminum:

Medium	Temperature	Velocity
	°C	*Feet per second*
Vulcanized rubber	0	177
Air	0	1,087
Oxygen	0	1,041
Hydrogen	0	4,220
Lead	20	4,030
Water	15	4,760
Copper	20	11,700
Hardwood (9-percent MC)	20	14,400
Aluminum	20	16,700
Iron	20	16,800

Longitudinal velocity of sound in these hardwood specimens averaged 1,100 fps less than in the loblolly pine veneer reported by Koch and Woodson (1968), and the individual test specimens had a smaller range, i.e., 11,000 to 17,200 fps for hardwood and 9,000 to 21,500 fps for southern pine. Yet six hardwood species did have a higher average than the pine veneer. Species averages ranged from 12,300 fps for blackjack oak to 16,100 fps for yellow-poplar (table 9-15). For each species, four or five other species had velocity-of-sound averages that were not significantly different (table 9-16); oak species could not be separated from non-oak species based on statistical differences in velocity of sound.

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[11] Price, E.W. 1980. Modulus of elasticity of small-diameter hardwoods growing on southern pine sites. Final Report FS-SO-3201-1.64, dated April 24, 1980, on file at the South. For. Exp. Stn., U.S. Dep. Agric., For. Serv., Pineville, La.

TABLE 9-15.—*Properties of 1-inch-square by 28-inch-long specimens taken from small-diameter hardwoods* (Price, text footnote[11])

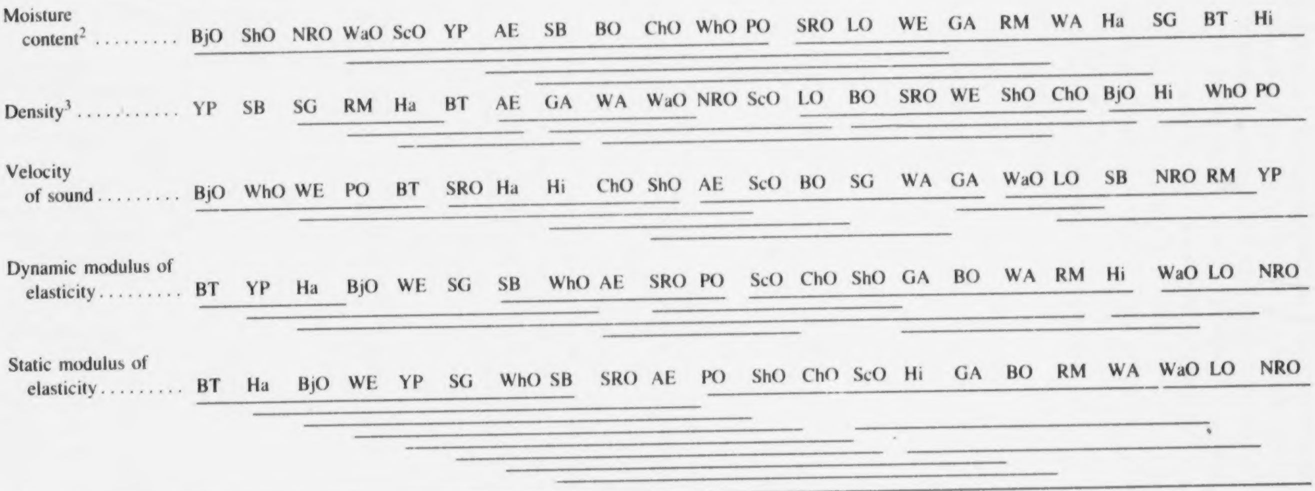
Species	Code for table 9-16	Moisture content	Density[1]	Velocity of sound	Modulus of elasticity		
					Dynamic	Static	Book[2]
		Percent	*Pcf*	*Fps*	*Million psi*		
Ash, green	GA	9.5	41.3	14,900	2.20	1.80	1.66
Ash, white	WA	9.6	43.4	14,600	2.21	1.90	1.74
Elm, American	AE	9.2	40.1	14,200	1.92	1.54	1.34
Elm, winged	WE	9.4	46.4	12,600	1.74	1.37	1.65
Hackberry	Ha	9.6	38.5	13,500	1.70	1.30	1.19
Hickory, true	Hi	9.7	52.1	13,600	2.30	1.79	2.22
Maple, red	RM	9.5	36.5	16,000	2.22	1.90	1.64
Oak, black	BO	9.3	45.5	14,300	2.20	1.83	1.64
Oak, blackjack	BjO	9.0	49.1	12,300	1.74	1.35	—
Oak, cherrybark	ChO	9.3	48.1	13,800	2.15	1.73	2.28
Oak, laurel	LO	9.4	44.4	15,400	2.50	2.08	1.69
Oak, northern red	NRO	9.1	44.0	15,900	2.64	2.32	1.82
Oak, post	PO	9.3	53.0	12,600	2.01	1.64	1.51
Oak, scarlet	ScO	9.1	44.0	14,300	2.13	1.75	1.91
Oak, Shumard	ShO	9.0	46.4	14,000	2.15	1.68	—
Oak, southern red	SRO	9.4	46.3	13,300	1.93	1.54	1.49
Oak, water	WaO	9.1	43.7	15,400	2.43	2.07	2.02
Oak, white	WhO	9.3	52.1	12,300	1.87	1.48	1.78
Sweetbay	SB	9.3	30.7	15,700	1.79	1.53	—
Sweetgum	SG	9.7	35.2	14,600	1.77	1.45	1.64
Tupelo, black	BT	9.7	39.0	12,700	1.50	1.21	1.20
Yellow-poplar	YP	9.1	27.1	16,100	1.67	1.43	1.58

---

[1] Based on volume at test and ovendry weight.

[2] From table 10-6 (at 12 percent moisture content).

TABLE 9-16.—*Among-species comparisons of properties, using Duncan's multiple range test. Property value increases from left to right, and those species underscored by the same line are not significantly different at the 0.05 level of probability.*[1] (Price, text footnote[11])



Moisture content[2]	BjO	ShO	NRO	WaO	ScO	YP	AE	SB	BO	ChO	WhO	PO	SRO	LO	WE	GA	RM	WA	Ha	SG	BT	Hi
Density[3]	YP	SB	SG	RM	Ha	BT	AE	GA	WA	WaO	NRO	ScO	LO	BO	SRO	WE	ShO	ChO	BjO	Hi	WhO	PO
Velocity of sound	BjO	WhO	WE	PO	BT	SRO	Ha	Hi	ChO	ShO	AE	ScO	BO	SG	WA	GA	WaO	LO	SB	NRO	RM	YP
Dynamic modulus of elasticity.........	BT	YP	Ha	BjO	WE	SG	SB	WhO	AE	SRO	PO	ScO	ChO	ShO	GA	BO	WA	RM	Hi	WaO	LO	NRO
Static modulus of elasticity.........	BT	Ha	BjO	WE	YP	SG	WhO	SB	SRO	AE	PO	ShO	ChO	ScO	Hi	GA	BO	RM	WA	WaO	LO	NRO

---

[1] For species codes, see table 9-15.
[2] At test, ovendry-weight basis.
[3] Of test specimens.

For these dry hardwood specimens, which averaged 1 inch square in cross section and 28 inches long, the relationship between dynamic and static modulus of elasticity is expressed by the regression expression:

$$E_s = -2.05 + 0.92E_d \qquad (9\text{-}21)$$

where E_s is static modulus of elasticity, psi. This relationship accounted for 95 percent of observed variation, i.e., $R^2 = 0.95$ (fig. 9-24).

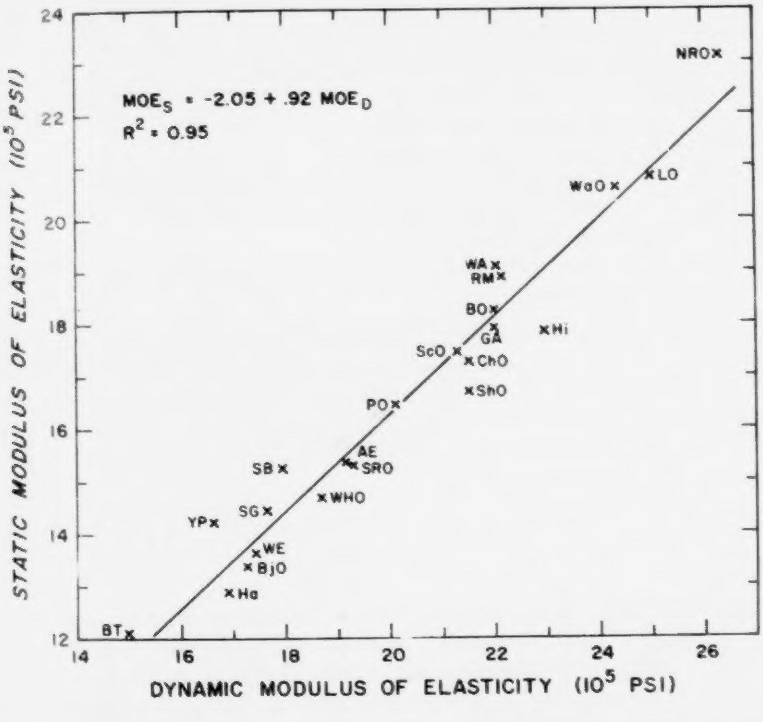


Figure 9-24.—Linear regression of static modulus of elasticity over dynamic modulus based on mean values for dry stemwood cut from small southern hardwoods of 22 species. See table 9-15 for species code. (Drawing after Price, text footnote[11])

Transverse vibrations in wood have also been employed to nondestructively evaluate strength properties in wood. Two methods have been used. In the first, the plank is driven into forced transverse vibration and its resonant frequency measured (Jayne 1959; James 1964; Miller and Tardiff 1967; Miller 1968). For a beam, the relationship is as follows:

$$E_d = \frac{f_n^2 W L^3}{c^2 I g} \tag{9-22}$$

where

E_d = dynamic modulus of elasticity, psi
f_n = resonance frequency, cycles per second
W = weight of beam, pounds
L = length of beam, inches
c = constant dependent upon mode of support (e.g., c = 1.57 for beams simply supported at the ends)
I = moment of inertia, inches^4
g = acceleration due to gravity (386 inches per second per second)

In a second method (Pellerin 1965; Marra et al. 1966), the plank to be evaluated is simply supported at the two ends and started by a single impact into free transverse vibration. With this method, the modulus of rupture is inversely proportional to the energy dissipation as measured by the rate of decay, or logarithmic decrement (δ) of the vibrating body; that is, as modulus of rupture increases, δ decreases.

$$\delta = \frac{1}{n} \ln_e \frac{A_1}{A_n} \tag{9-23}$$

where A_1 and A_n are the amplitudes of two oscillations n cycles apart on a vibration decay curve. In practice, the mechanism that senses the two amplitudes A_1 and A_n is set to trigger at amplitudes such that the natural logarithm of A_1/A_n is equal to unity. Under these conditions the number of oscillations, n, which occur between these two amplitudes is the reciprocal of the logarithmic decrement, δ. To apply the method, it is first necessary to empirically establish a regression relationship between the logarithmic decrement and the modulus of rupture of the class of planks to be evaluated.

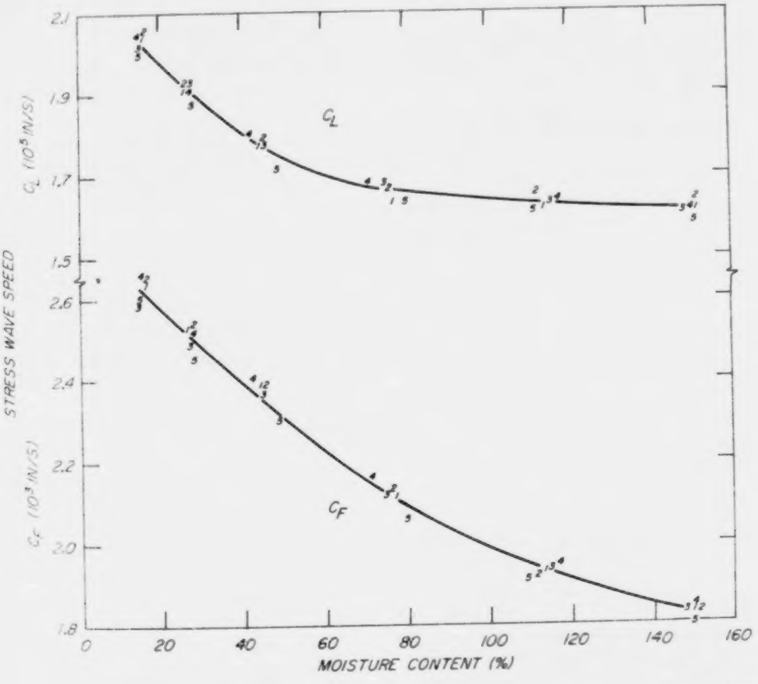
Flexural stress waves, i.e., those induced by transverse bending, travel along a beam at speed c_f, given approximately by:

$$c_f = \frac{2\pi K}{\lambda} \sqrt{E_d \sigma} \tag{9-24}$$

where K is radius of gyration, and λ is wavelength (Kolsky 1963). The dynamic flexural E_d may be estimated from measurement of C_f, λ, K, and σ. For wood, the density σ is based on the combined weight of wood and moisture.

Gerhards (1975) concluded that on dry wood the longitudinal-stress-wave technique yields the highest estimate of modulus of elasticity, the transverse vibration method an intermediate value, and the static-bending technique the lowest value.

When applied to moist sweetgum wood, the speed of both types of stress waves (longitudinal and flexural from transverse vibration) increased curvilinearly, but at different rates, as moisture content decreased (fig. 9-25). Modulus of elasticity calculated from the longitudinal stress wave formula (eq. 9-20) was strongly dependent on moisture content over the range studied, i.e., 15 to 150 percent of dry weight. Modulus of elasticity calculated from the flexural-stress-wave formula (eq. 9-24) did not change much at moisture contents above 50 percent (Gerhards 1975).



M-142-632

Figure 9-25.—Effect of moisture content on speed of longitudinal (C_L) and flexural (C_f) stress waves in 8-foot-long 2- by 4s of clear sweetgum sapwood. Data points are indicated by specimen numbers. (Drawing after Gerhards 1975.)

9-6 LITERATURE CITED

American Society for Testing and Materials. 1976. Standard recommended practice for spectrophotometry and description of color in CIE 1931 system. Recommended practice E308-66. 1976 Annual Book of ASTM Standards, Part 46, p. 253-270. Philadelphia, Pa.: ASTM.

Beall, F. C., P. R. Blankenhorn, and G. R. Moore 1974. Carbonized wood—physical properties and use as an SEM preparation. Wood Sci. 6:212-219.

Beckwith, J. R., III. 1974. An illustration of wood color measurement. Ga. For. Res. Pap. 74, 6 p. Macon, Ga.: Ga. For Res. Counc.

Beckwith, J. R., III. 1979. Theory and practice of hardwood color measurement. Wood Sci. 11:169-175.

Bois, P. J. 1970. Gray-brown chemical stain in southern hardwoods. U.S. Dep. Agric. For. Serv., For. Prod. Util. Tech. Rep. No. 1, 4. p. State and Priv. For., Madison, Wis.

Brown, J. H., R. W. Davidson, and C. Skaar. 1963. Mechanism of electrical conduction in wood. For. Prod. J. 13:455-459.

Chudinov, B.S. 1968. (Theory of thermal treatment of wood.) Izdatel'stvo "Nauka", Moscow, Akad. Nauk, SSSR. pp. 37, 70-104.

Clark, J.W. 1957. A gray non-fungus seasoning discoloration of certain red oaks. South. Lumberman 194(2418): 35-38.

Clark, J.D. and J.W. Williams. 1933. The electrical conductivity of commercial dielectrics and its variation with temperature. J. Phys. Chem. 37:119-131.

Davis, T.C. and H.O. Beals. 1977a. Color in sweetgum wood. Agric. Exp. Stn. Circ. 231, 15 p. Auburn, Ala.: Auburn Univ.

Davis, T.C. and H.O. Beals. 1977b. Internal discoloration of sweetgum. Agric. Exp. Stn. Circ. 234, 16 p. Auburn, Ala., Auburn Univ.

Dunlap, F. 1912. The specific heat of wood. U.S. Dep. Agric. For. Serv., Bull. 110. 28 p.

Fergus, C.L. 1955. Frost cracks on oak. Phytopathol. 46(5):297.

Fleischer, H.O. 1951. Advantages in heating veneer logs in long-log lengths. Wood 6(9):50.

Galligan, W.L. and Courteau, R.W. 1965. Measurement of elasticity of lumber with longitudinal stress waves and the piezoelectric effect of wood. *In* Proc. of second symposium on the non-destructive testing of wood, pp. 223-244. Pullman, Wa.: Wa. State Univ.

Gerhards, C.C. 1975. Stress wave speed and MOE of sweetgum ranging from 150 to 15 percent MC. For. Prod. J. 25(4):51-57.

Hardy, A.C. 1936. Handbook of colorimetry. Cambridge, Mass.: Mass. Inst. of Technol., The Technol. Press. 87 pp.

Hearle, J.W.S. 1953. The electrical resistance of textile materials. J. Textile Inst. 44(4):T117-T-199.

Hearmon, R.F.S. and J.N. Burcham. 1955. Specific heat and heat of wetting of wood. Nature 176(4490):978.

Heebink, B.G. and H.H. Haskell. 1962. Effect of heat and humidity on the properties of high-pressure laminates. For. Prod. J. 12:542-548.

Hepting, G.H., E.R. Roth, and R.F. Luxford. 1952. The significance of the discolorations in yellow-poplar veneers. U.S. Dep. Agric. For. Serv., FPL Rep. No. 1375. 10 p.

Hopkins, W.C., and W.C. Kelso, Jr. 1951. Kiln-drying of hickory handle stock; pilot tests of drying schedules. South. Lumberman 182(2285):40-42.

Hunter, A.G. and J.F. Goggans. 1968. Variation in specific gravity, diameter growth, and colored heartwood of sweetgum in Alabama. Tappi 51:76-79.

James, W.L. 1964. Vibration, static strength, and elastic properties of clear Douglas-fir at various levels of moisture content. For. Prod. J. 14:409-413.

James, W.L. 1975a. Dielectric properties of wood and hardboard: variation with temperature, frequency, moisture content, and grain orientation. U.S. Dep. Agric. For. Serv. Res. Pap. FPL 245. 32 p.

James. W.L. 1975b. Electric moisture meters for wood. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. FPL-6. 27 p.

Jayne, B.A. 1959. Indices of quality—vibrational properties of wood. For. Prod. J. 9:413-416.

Judd, D.B. 1933. The 1931 I.C.I. standard observer and coordinate system for colorimetry. J. of the Opt. Soc. of Am. 23:359-374.

Kanter, K.R. 1957. (The thermal properties of wood.) Derev. Prom. 6(7):17-18.

Koch, P. 1969. Specific heat of ovendry spruce pine wood and bark. Wood Sci. 1:203-213.

Koch, P. 1972. Utilization of the southern pines. U.S. Dep. Agric. For. Serv., Agric. Handb. 420. 1663 p. 2 vol. U.S. Govt. Print. Off., Washington, D.C.

Koch, P. and G.E. Woodson. 1963. Laminating butt-jointed, log-run, southern pine veneers into long beams of uniform high strength. For. Prod. J. 18(10):45-51.

Kollmann, F. and L. Malmquist. 1956. Über die Wärmeleitzahl von Holz und Holzwerkstoffen. Holz als Roh- und Werkstoff 14:201-204.

Kolsky, H. 1963. Stress waves in solids. 2nd ed. 213 p. New York, N.Y.: Dover Publ.

Kubler, H. 1977. Formation of checks in tree stems during heating. For. Prod. J. 27(1):41-46.

Kubler, H., L. Liang, and L.S. Chang. 1973. Thermal expansion of moist wood. Wood and Fiber 5:257-267.

Langwig, J.E. and C. Skaar. 1975. Electrical resistivities of 18 Venezuelan and 13 North American woods. Wood Sci. 8:350-354.

Lemoine, T.J. and P. Koch. 1975. Coefficient of friction of dry slash pine and southern red oak on three tension-grip facings. Wood Sci. 7:182-184.

Lemoine, T.J., McMillin, C.W., and Manwiller, F.G. 1970. Wood variables affecting the friction coefficient of spruce pine on steel. Wood Sci. 2: 144-148.

Lewis, W.C. 1967. Thermal conductivity of wood-base fiber and particle panel materials. U.S. Dep. Agric. For. Serv., Res. Pap. FPL 77. 12 p.

Lin, R.T. 1965. A study of electrical conduction in wood. Ph.D. Thesis. 196 p. Syracuse, N.Y.: State Univ. Coll. of For.

Lin, R.T. 1967. Review of the electrical properties of wood and cellulose. For. Prod. J. 17(7):54-66.

Luxford, R.F. and L.W. Wood. 1953. Survey of strength and related properties of yellow-poplar. U.S. Dep. Agric. For. Serv., FPL Rep. No. 1610. 44 p.

MacLean, J.D. 1941. Thermal conductivity of wood. Heating, Piping and Air Conditioning 13:380-391.

Marra, G.G., Pellerin, R.F. and W.L. Galligan. 1966. Nondestructive determination of wood strength and elasticity by vibration. Holz als Roh-und Werkstoff 10:460-466.

McMillen, J.M. 1975. Physical characteristics of seasoning discolorations in sugar maple sapwood. U.S. Dep. of Agric. For. Serv., Res. Pap. FPL 248. 31 p.

McMillen, J.M. 1976. Control of reddish-brown coloration in drying maple sapwood. U.S. Dep. Agric. For. Serv., Res. Note FPL-0231. 8 p.

McMillin, C.W. 1969. Specific heat of ovendry loblolly pine wood. Wood Sci. 2:107-111.

McMillin, C.W. 1970. Specific heat of some ovendry chemical constituents of loblolly pine wood. Wood Sci. 3:52-53.

McMillin, C.W., T.J. Lemoine, and F.G. Manwiller. 1970a. Friction coefficient of oven-dry spruce pine on steel, as related to temperature and wood properties. Wood and Fiber 2:6-11.

McMillin, C.W., T.J. Lemoine, and F.G. Manwiller. 1970b. Friction coefficient of spruce pine on steel—a note on lubricants. Wood Sci. 3:100-101.

Miller, D.G. 1968. Nondestructive testing of joists by a vibrational technique. For. Prod. J. 18(2):25-28.

Miller, D.G. and Y. Tardif. 1967. Development of a vibration grader and comparison of vibration grading with visual and mechanical grading. Can. Dep. For. and Rural Develop. Publ. 1208, 24 p.

Murase, Y. 1977. Effect of surface roughness on friction between wood and steel. J. Jap. Wood Res. Soc. 23(2):76-81.

Murase, Y. 1980. (Frictional properties of wood at high sliding speed.) J. Jap. Wood Res. Soc. 26:61-65.

Murphey, W.K., and K.R. Masters. 1978. Gross heat of combustion of northern red oak (*Quercus rubra*) chemical components. Wood Sci. 10:139-141.

Okoh, I.K.A. 1976. Moisture sorption and electrical resistivity of some woods and barks. Ph.D. thesis. State Univ. of N.Y. Coll. of Environ. Sci. and For., Syracuse, N.Y. 183 p.

Pellerin, R.F. 1965. A vibrational approach to nondestructive testing of structural lumber. For. Prod. J. 15:93-101.

Peters, C.C. and J.D. Cumming. 1970. Measuring wood smoothness: a review. For. Prod. J. 20(12):40-43.

Piirto, D.D. and W.W. Wilcox. 1978. Critical evaluation of the pulsed-current resistance meter for detection of decay in wood. For. Prod. J. 28(1):52-57.

Place, T.A. and T.M. Maloney. 1975. Thermal properties of dry wood-bark multilayer boards. For. Prod. J. 25(1):33-39.

Price, E.W. 1982. Chemical stains in hackberry can be prevented. South. Lumberman 243(3019):13-15.

Ratcliff, E.H. 1964. A review of thermal conductivity data—Part I. Wood 29(7):49-51; Part 2, 29(8):46-49; Part 3, 29(9):50-54.

Rucker, T.W., and W.R. Smith. 1961. Forced-air drying of lumber—research and experimental. For. Prod. J. 11:390-394.

Sachs, I.B., J.C. Ward, and E.H. Bulgrin. 1966. Heartwood stain in red oak. Holz als Roh- und Werkstoff 24:489-497.

Safford, L.O., A.L. Shigo, and M. Ashley. 1974. Gradients of cation concentration in discolored wood of red maple. Can. J. of For. Res. 4:435-440.

Schneider, A. and F. Engelhardt. 1977. Comparative investigations on the thermal conductivity of wood-particle boards and bark boards. Holz als Roh- und Werkstoff 7:273-278.

Shigo, A.L. 1965. Decay and discoloration in sprout red maple. Phytopathol. 55:957-962.

Shigo, A.L. 1972. Successions of microorganisms and patterns of discoloration and decay after wounding in red oak and white oak. Phytopathol. 62:256-259.

Shigo, A.L. 1975. Heartwood and discolored wood. The North. Logger and Timber Proc. 24(2):28-29.

Shigo, A.L. and W.E. Hillis. 1973. Heartwood, discolored wood, and microorganisms in living trees. Annu. Rev. of Phytopathol. 11:197-222.

Shigo, A.L. and E.vH. Larson. 1969. A photo guide to the patterns of discoloration and decay in living northern hardwood trees. U.S. Dep. Agric. For. Serv., Res. Pap. NE-127. 100 p.

Shigo, A.L. and H.G. Marx. 1977. Compartmentalization of decay in trees. U.S. Dep. Agric. For. Serv., Agric. Inf. Bull. No. 405. 73 p. U.S. Govt. Print. Off., Washington, D.C.

Shigo, A.L. and A. Shigo. 1974. Detection of discoloration and decay in living trees and utility poles. U.S. Dep. Agric. For. Serv., Res. Pap. NE-294. 11 p.

Shortle, W.C., and E.B. Cowling. 1978. Development of discoloration, decay, and microorganisms following wounding of sweetgum and yellow-poplar trees. Phytopathology 68:609-616.

Shortle, W.C., A.L. Shigo, and J. Ochrymowych. 1978. Patterns of resistance to a pulsed electric current in sound and decayed utility poles. For. Prod. J. 28(1):48-51.

Skutt, H.R., A.L. Shigo, and R.A. Lessard. 1972. Detection of discolored and decayed wood in living trees using a pulsed electric current. Can. J. of For. Res. 2:54-56.

Smith, L.W. 1960. Heat sensitivity of the skin to wood and other materials. For. Prod. J. 10:170.

Southern Hardwood Lumber Manufacturers' Association. (n.d.) The southern hardwoods. 67 p. Memphis, Tenn.: South. Hardwood Lumber Manuf. Assoc.

Stamm, A.J. 1964. Wood and cellulose science. 549 p. N.Y.: Ronald Press Co.

Steinhagen, H. 1977. Thermal conductive properties of wood, green or dry, from −40° to +100°C: a literature review. U.S. Dep. of Agric. For. Serv., Gen. Tech. Rep. FPL-9. 10 p.

Tattar, T.A. 1974. Measurement of electric currents in clear, discolored, and decayed wood from living trees. Phytopathol. 64:1375-1376.

Teesdale, L.V. 1958. Thermal insulation made of wood-base materials. U.S. Dep. of Agric. For. Serv., For. Prod. Lab. Rep. No. 1740. 74 p.

U.S. Department of Agriculture, Forest Service. 1956. Wood . . . colors and kinds. U.S. Dep. Agric. For. Serv., Agric. Handb. No. 101. 36 p. U.S. Govt. Print. Off., Washington, D.C.

U.S. Department of Agriculture, Forest Service. 1974. Wood handbook: Wood as an engineering material. U.S. Dep. Agric. For. Serv., Agric. Handb. 72, rev. For. Prod. Lab., Madison, Wis.

Umehara, K., N. Minemura, and T. Suganuma. 1979. Photoinduced discoloration of northern red oak. J. Hokkaido For. Prod. Res. Inst. (327):15-16.

Venkateswaran, A. 1973. Effect of compression on electrical properties of wood and cellulose. Wood Sci. 5:230-234.

Venkateswaran, A. 1974. The interdependence of the lignin content and electrical properties of wood. Wood and Fiber 6:46-52.

Vick, C.B. 1965. Drying-rate curves for one-inch yellow-poplar lumber in low-temperature forced-air dryers. For. Prod. J. 15:500-504.

Vick, C.B. 1968. Low-temperature drying of 1-inch sweetgum. For. Prod. J. 18(4):29-32.

Vick, C.B. and M.A. Taras. 1969. Stain in red oak parquet flooring. For. Prod. J. 19(9):83-86.

Wangaard, F.F. 1943. The effect of wood structure upon heat conductivity. Trans. Am. Soc. Mech. Eng. 65(2):127-134.

Wangaard, F.F. 1969. Heat transmissivity of southern pine wood, plywood, fiberboard, and particleboard. Wood Sci. 2:54-60.

Ward, R.J. and C. Skaar. 1963. Specific heat and conductivity of particleboard as functions of temperature. For. Prod. J. 13:31-38.

Weatherwax, R.C., and A.J. Stamm. 1947. The coefficients of thermal expansion of wood and wood products. Trans. of the Am. Soc. Mech. Eng. 69:421-432.

10

Mechanical Properties

Major portions of data drawn from research by:

- American Plywood Association
- R. H. Atalla
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Mechanical Properties

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CHAPTER 10

Mechanical Properties

The load that a block of hardwood can carry is strongly affected by the direction in which the force is applied with relation to the direction of fiber alignment. Intrinsic wood properties of anatomical structure, chemical makeup, and specific gravity are also major determinants of the load-carrying capability of different species of wood. Additionally, treatment history of the wood affects its properties, i. e. , prior exposure to fungus, insect or woodpecker attack, radiation, chemical impregnation, seasoning degrade, or high temperatures all affect the performance of wood under load. Finally, certain characteristics of the service situation affect the ability of wood to support a load; such characteristics include rate of load application, duration of load, and atmospheric conditions of temperature, humidity, and air purity.

Under some conditions, the mechanical behavior of wood reflects the fact that it is a viscoelastic, time-dependent material rather than a purely elastic material. The explanation of such behavior lies in the heterogeneous amorphous-crystalline structure of the cell wall.

When lightly loaded for a short term, however, wood deforms according to Hooke's law; that is, the **strain** or deformation in a piece of wood is proportional to the applied **stress** or force per unit area. Within this elastic range, the ratio of stress/unit strain—an indication of stiffness—is termed the **modulus of elasticity**. Stress is commonly measured in pounds force per square inch of area, and strain is expressed as inch change in length per inch of length. Therefore modulus of elasticity has the units pounds/inch^2 ÷ inch/inch; i. e. , pounds per square inch. When the limit of proportionality or **proportional limit** is exceeded, wood takes a permanent set. As the applied load is further increased, a maximum is reached and failure occurs; stress at failure is termed the **maximum strength** or simply **strength**.

For a specimen loaded in bending, the maximum fiber stress at failure (compression or tension) calculated from the applied load and sample dimensions is termed **modulus of rupture**.

Many southern hardwoods are prized for their toughness and find use as tool handles and in sports gear; **toughness** is assessed by measuring the energy required to rapidly cause complete failure in a centrally loaded bending specimen.

10-1 WOOD STRENGTH AS AFFECTED BY ANATOMY AND DENSITY

Strength properties of hardwoods are strongly influenced by their anatomical properties. For example, Hill (1954) found that the bending strength of northern red oak is positively correlated with percentage of fiber area and latewood area, but negatively correlated with vessel area in earlywood as viewed in transverse section.

Because fibers comprise most of the volume in hardwoods, their behavior under stress strongly affects the mechanical behavior of whole wood. Transfer of a load applied to wood induces shear forces between the very large number (billions per cubic foot) of overlapping, tapered wood fibers.

FAILURE IN COMPRESSION

Hardwoods loaded in **compression parallel to the grain** develop visibly well-defined patterns of buckling failures. On the tangential faces of failed rectangular specimens, the lines of failure make an angle of 45° to 60° to the axial (grain) direction (fig. 10-1A). In round specimens, the failure lines from a single plane (fig. 10-1B) or double helix (fig. 10-1C).

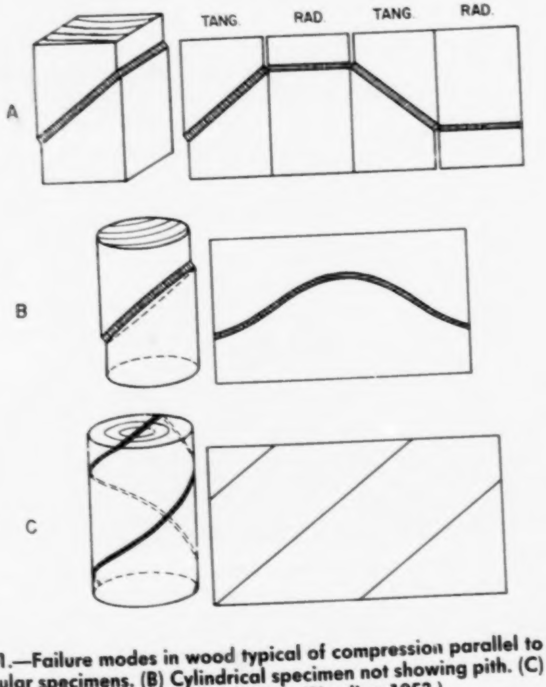

Figure 10-1.—Failure modes in wood typical of compression parallel to the grain. (A) Rectangular specimens. (B) Cylindrical specimen not showing pith. (C) Pith-centered cylindrical specimen. (Drawing after Frey-Wyssling 1953.)

Côté and Hanna[1] found that the failure lines result from intercellular separation at ray/fiber interfaces (fig. 10-2 top) and between fibers (fig. 10-2 bottom left); shear stresses accompany these deformations causing intra-wall failures between S1 and S2 layers (fig. 10-2 top right). Macroscopic buckling of fibers is

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[1] Côté, W. A. , and R. B. Hanna. Investigation into hardwood fracture modes observed at the ultrastructural level. Fin. Rep. FS-SO-3201-23, dated January 20, 1982. U. S. Dep. Agric. For. Serv. , South. For. Exp. Stn. , Pineville, La. See also Côté and Hanna (1983).

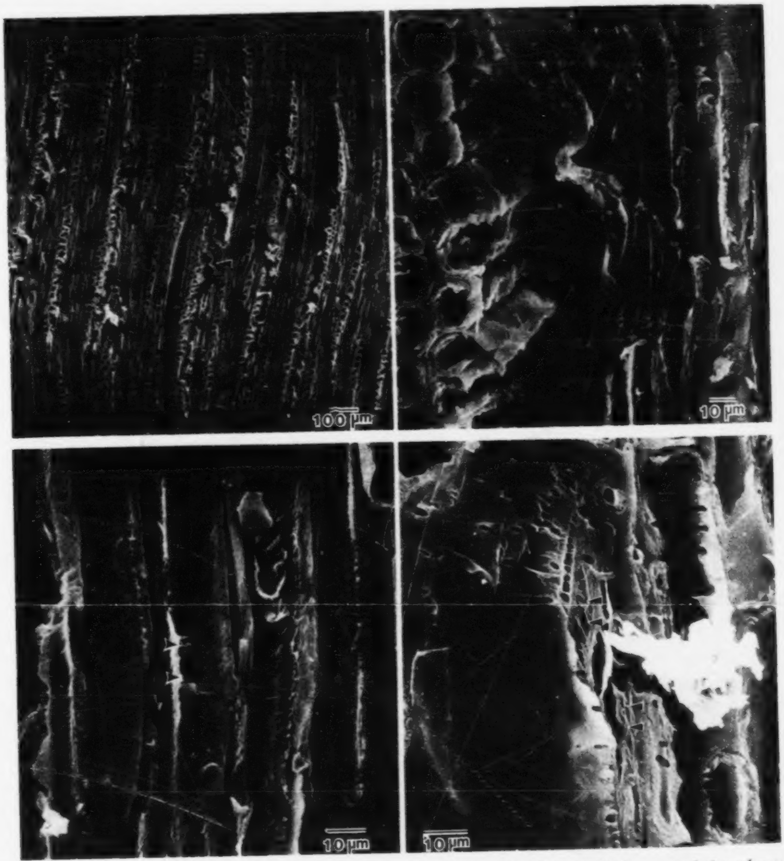

Figure 10-2.—Failure in compression parallel to the grain. (Top left) Tangential surface of southern red oak showing start of gross buckling and initiation of separation adjacent to rays; see arrow. (Top right) Failure area in top left figure enlarged to show ray parenchyma (R) separated from fiber (F). (Bottom left) Hickory section showing deformations in S3 layer of cell walls (arrows) and separation of fibers at or near the middle lamella. (Bottom right) Initiation of buckling and failure within fiber wall (arrow) of southern red oak viewed in approximately tangential section. (Scanning electron micrographs from Côté and Hanna[1].)

preceded by minute deformations of cell walls (fig. 10-2 bottom right); intracellular deformations or slip planes are easily seen (fig. 10-2 bottom left). The ray/fiber interface appears to be a weak link at which failure in compression parallel to the grain is frequently initiated.

For southern pine, the strength and stiffness of wood loaded in compression parallel to the grain—as measured by the indices of maximum strength/specific gravity and modulus of elasticity/specific gravity—have a negative linear correlation with the sine of the fibril angle; i. e. , the strength indices are lower for wood of high fibril angle than for wood of low fibril angle (Garland 1939; Koch 1972, p. 396). No comparable data on southern hardwoods are published, but similar relationships probably exist.

Application of **compressive force perpendicular to the grain** direction causes fiber walls to bend inward or to distort sideways, and vessels to collapse, thereby altering transverse shapes of tissue elements (fig. 10-3). If loaded in radial compression, hardwood rays resist deformation; when loaded in the tangential direction, however, ray structures are not effective in resisting distortion but latewood in some species may stiffen the weaker earlywood of each annual ring.

McMillin[2] found that in southern red oak compressed parallel to the rays (figs. 10-3AB), failure typically occurs in the parenchyma and fiber cells adjoining large earlywood vessels. Ray cells, while slightly deformed, strengthen the structure through support as columns. With heavy compression, parenchyma and fiber cells fail in shear and rays buckle. At extreme levels, the entire structure collapses onto the supportive cells in the adjacent annual ring and rays exhibit multiple buckling.

When strained at 45° to the rays, the cellular structure tends to deform and slip in a plane defined by the annual ring increment. At heavy strain levels, parenchyma and fibers fail in shear. Rays, while deformed, provide some support for the adjacent structure. At extreme strain levels, shear failures result in a plane of total fracture and in some cases physical separation of the adjoining pieces.

When loaded perpendicular to the rays (fig. 10-3C), initial strain causes the generally round vessels to deform to an oval shape. Deformation is more or less evenly distributed throughout the cross-section. At moderate levels, parenchyma and fiber cells adjacent to vessels fail by buckling or by bending. At extreme compression, vessels collapse onto the supportive structure of rays.

A similar pattern of deformation and failure occurs in sweetgum. However, sweetgum is diffuse-porous and stresses are more evenly distributed throughout the section. Thus, deformation and cell failure occur in less well-defined planes.

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[2] McMillin, C. W. Deformation and fracture surfaces in southern hardwoods strained in tension, compression, and shear—a pictorial analysis. Fin. Rep. FS-SO-3201-2, dated Sept. 23, 1981. U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Pineville, La.

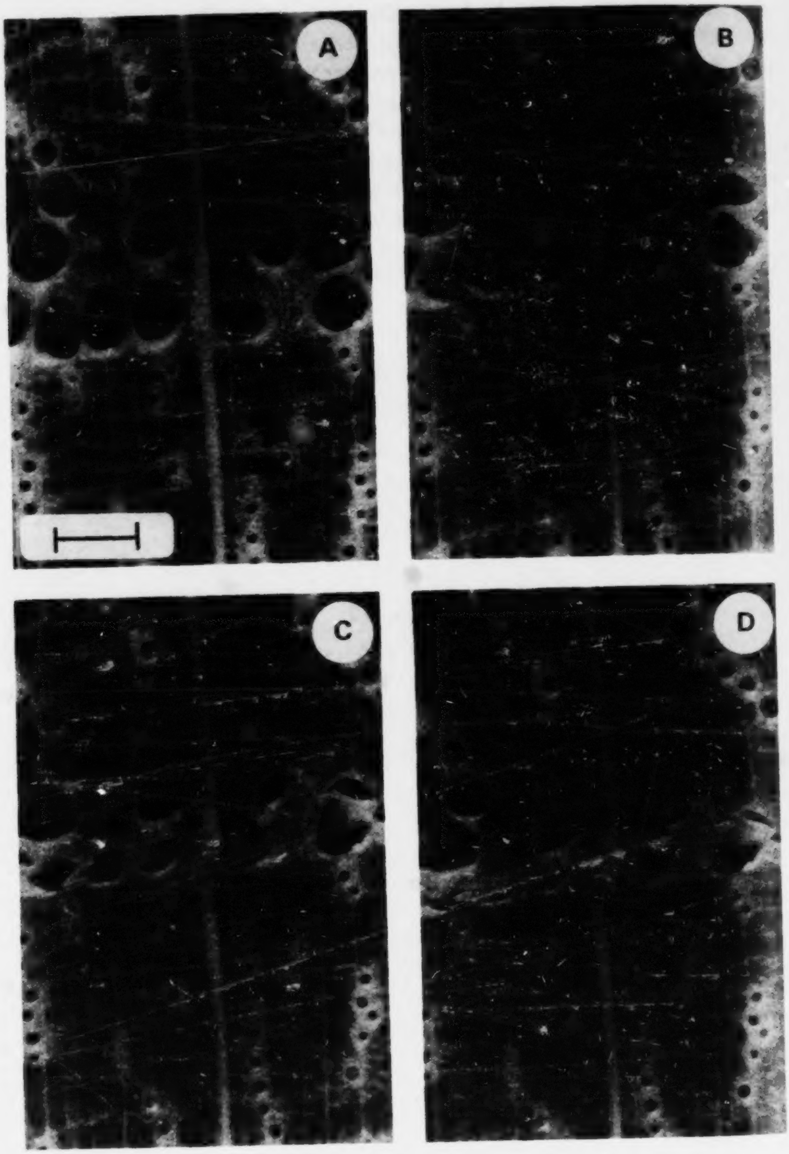

Figure 10-3A.—Transverse surface of southern red oak compressed perpendicular to the grain with the load applied parallel to the rays. (A) Unstrained. (B) Moderate strain. (C) Heavy strain. (D) Extreme strain. The scale mark shows 0.5 mm. (Micrograph from C. W. McMillin[2].)

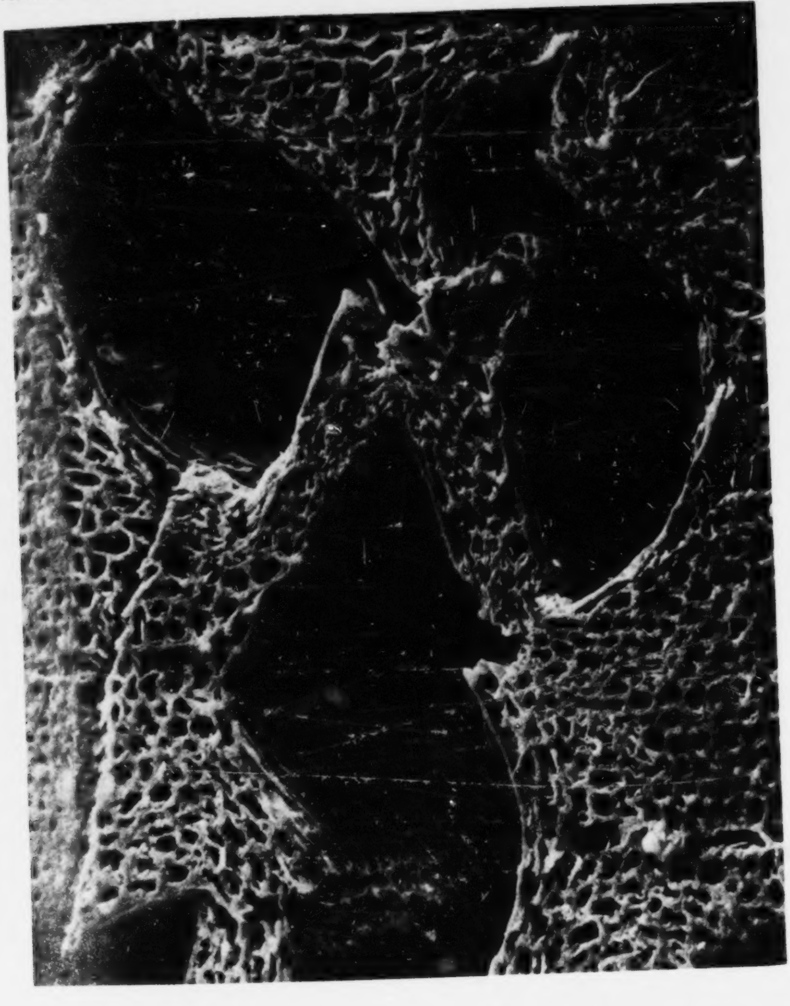

Figure 10-3B.—Vessel collapse at extreme level of compression perpendicular to the grain with load applied parallel to rays of southern red oak. (Scanning electron micrograph from C. W. McMillin[2].)

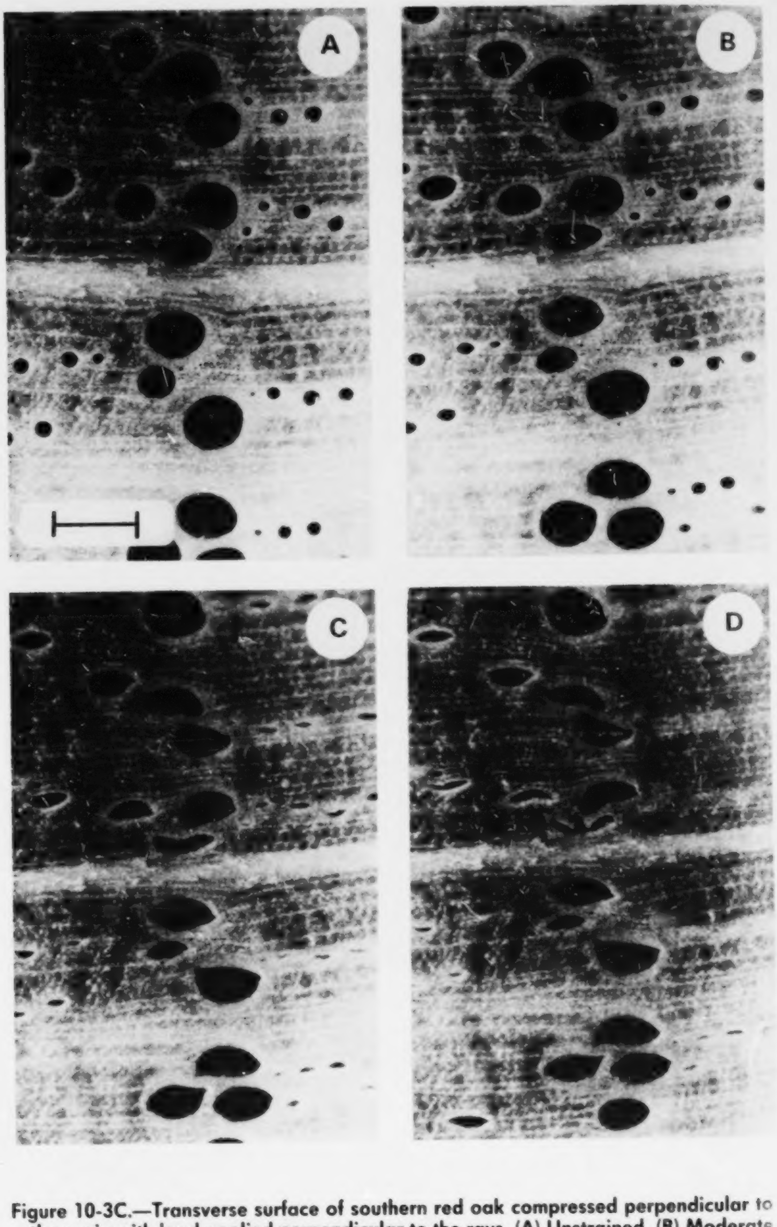

Figure 10-3C.—Transverse surface of southern red oak compressed perpendicular to the grain with load applied perpendicular to the rays. (A) Unstrained. (B) Moderate strain. (C) Heavy strain. (D) Extreme strain. Scale mark shows 0.5 mm. (Micrographs from C. W. McMillin[2].)

All factors considered, modulus of elasticity in the longitudinal direction exceeds that in the radial direction by about 10 times, and that in the tangential direction by about 20 times. For example, E_T:E_R:E_L ratios for sweetgum and yellow-poplar at 11 percent moisture content are .050:.089:1 and .043:.092:1, respectively (U.S. Department of Agriculture, Forest Service 1974, p. 4-6). Hardwoods loaded in compression in the radial direction not only have greater modulus of elasticity, but also greater strength than when loaded in the tangential direction (Stern 1944a). Kennedy (1968) concluded that the ratio of compressive strength of radially loaded to tangentially loaded specimens increased with increasing ray volumes and decreased with decreasing latewood percentage and differential density within an increment.

In some wood product applications, the direction of important stresses may not coincide with the natural axes of fiber orientation in the wood. This may occur by choice in design, by the way the wood was removed from the log, or because of grain irregularities that occurred during growth. Mathematical and graphical methods to predict elastic properties and strength of wood in directions other than along the grain and at any angle to the annual rings are given in the Wood Handbook (U.S. Department of Agriculture, Forest Service 1974, p. 4-27 and 4-29).

Readers interested in mathematical modelling will find Goodman and Bodig's (1971) study useful; they concluded that Hankinson's formula seems to be the best predictor of compression strength of wood at an angle to the grain. When this formula is combined with a sine function for radial-tangential direction, the compression strength at any angle to grain and annual rings can be predicted. While tneir formula was derived from compression data, the authors believe it equally valid for prediction of tensile strength.

Table 10-6 gives most species-average data needed for application of such mathematical models.

FAILURE IN TENSION

Hardwoods fabricated into fiber products, flakeboards, or solid-wood products frequently serve in applications where they are loaded in tension; examples include paper bags, flakeboard roof sheathing and chords in roof trusses. Regardless of product form, tensile failure parallel to the grain results from breaking individual fiber walls in tension. Mark (1965) has provided a detailed stress analysis of coniferous tracheids under tension. No similar analysis of hardwood fibers in tension has been published.

Although the tensile strength of dry whole wood is considerably greater than that of wood in the saturated or green condition, single wood fibers are stronger in tension when wet than when dry (Wardrop 1951). The greater tensile strength of wet fibers is attributed to a more equal distribution of load over the cellulose chains constituting the microfibrils. In the dry condition lateral bonding between chains leads to localized stress concentrations and rupture of the wall.

In southern pine, tensile strength of micro-specimens of solid wood is negatively correlated with their fibril angle (Garland 1939; Koch 1972, p. 396; Manwiller and Godfrey 1973; Page and El-Hosseiny 1976). No comparable data are published for southern hardwoods, but Tamolang et al. (1967) found that tensile strengths per unit area of cell wall of individual fibers of 17 species of tropical hardwoods were positively correlated ($R^2 = 0.888$) with the cosine of their fibril angle.

Côté and Hanna[1] found that failures in hardwood fibers stressed parallel to the grain in tension are complex (fig. 10-4). Generally, tension produces transwall failure which follows the S2 fibrillar angle in those cells having a thick S2 layer (fig. 10-4 bottom right). The "unwinding" phenomenon probably results from slippage between microfibrils. There is also evidence of intra-wall failure in the S1, allowing the fiber core (S2 and S3) to pull out as seen in figures 10-4 bottom and 5-74). In cells with lesser S2 cell wall area, such as oak earlywood, abrupt transwall failures may be found.

Kellogg and Wangard (1964) found that individual fibers drawn from chips pulped by the kraft process had high tensile strength; strength was positively correlated with the pulp's permanganate number, which is in turn positively correlated with lignin content of the pulp. Strengths observed in single fibers of two southern hardwoods were as follows:

Species and permanganate number	Fiber tensile strength
	Psi
Sweetgum	
8.4	39,000
9.0	40,300
11.8	59,200
14.6	57,500
16.4	57,200
White Oak	
3.8	37,600
10.7	36,800
11.5	55,000
15.0	55,800

Paper may have only one-fourth the tensile strength of the fibers from which it is made (Przybysz and Napiorkowska (1976), but tensile and bursting strength of high-density sheets were found by Kellogg and Wangaard (1964) to be highly correlated with fiber strength. The influence of fiber strength on these properties was found negligible at low sheet density.

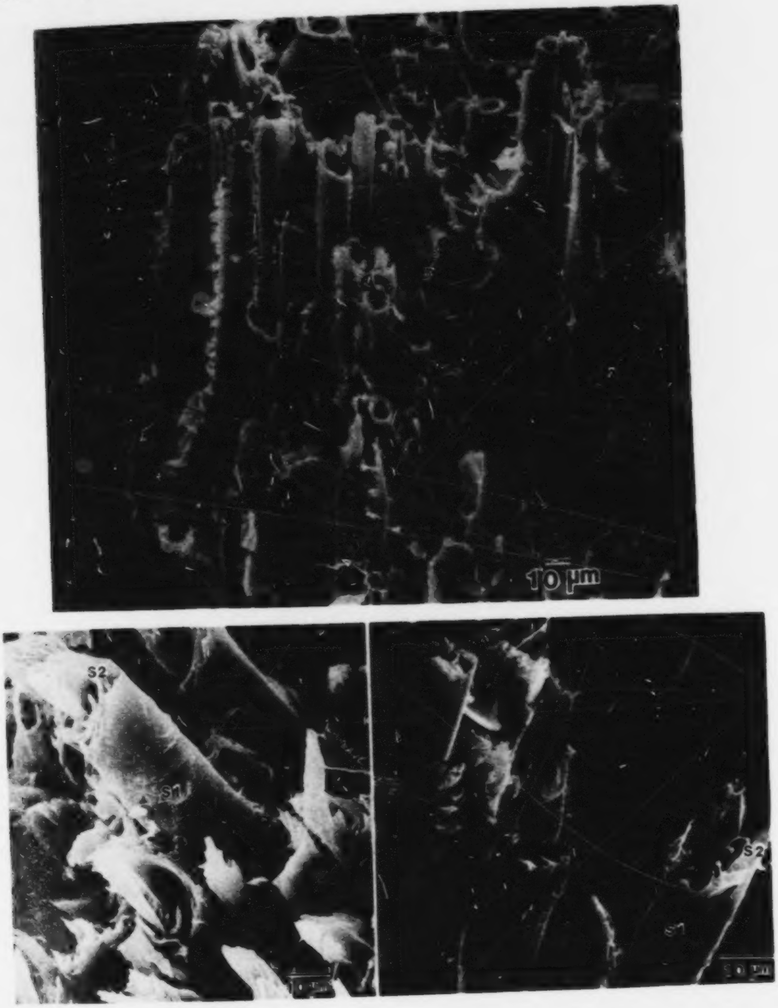

Figure 10-4.—Hardwood failures in tension parallel to the grain. (Top) Sweetgum, in which transwall fractures predominate because of thin cell walls; some intra-wall failures evident, mostly occurring at the S1/S2 interace. (Bottom left) southern red oak, showing individual fibers projecting out of the failure zone—typical of dense hardwoods. Intra-wall failure predominates; S1 and S2 microfibrillar orientation evident. (Bottom right) Hickory, showing unwinding of fibers; intra-wall failures at S1/S2 interface predominate while transwall failure is evident at S2 regions of cell walls. (Scanning electron micrographs from Côté and Hanna[1].)

Solid wood of small dimension has less tensile strength per square inch of cross section than an individual fiber of the species, but more than bending specimens of larger size would indicate. For example, Richards (1958) found that straight-grained slats of white ash and red oak machined to about 1/10-inch thickness and approximately 7/8-inch width had tensile strengths as follows, when strained parallel to the grain:

Statistic	White ash	Red oak (species not identified)
Number of specimens	84	113
Specific gravity (basis of ovendry volume and weight)	0.64	0.70
Average moisture content (percent of dry weight)	7.9	6.2
Average tensile strength (psi)	26,335	24,346
Coefficient of variation (percent)	19.6	17.0

Tensile properties of flakes used on the surface of flakeboards are major determinants of the strength and stiffness of such boards. In an evaluation of dry rotary-cut sweetgum veneer flakes measuring 3 inches along the grain, 3/8-inch wide, and 0.015-inch thick, (Price 1976) found that at gage lengths (distance between grips) of 0.50 to 1.25 inch tensile strength averaged 9,400 psi for the smaller gage-length classes and 8,000 psi for the upper range of gage lengths. Modulus of elasticity averaged from 460,000 psi to 675,000 psi. These values are substantially lower than those for solid wood of this species (table 10-6). Price concluded that the discrepancy between solid wood values and flake values could be caused, in part, by the possibility of grain slope through the thickness of each flake, cell damage occurring during the machining process, and inability to measure correct strain by the methods used.

Tensile strengths of flakes with longitudinal grain direction at an angle to direction of stress can be accurately predicted by use of Hankinson's formula (Price 1974).

When stressed in tension perpendicular to the grain, woods with prominent rays have greater strength in the radial than in the tangential direction. From tests on California black oak (*Quercus kelloggii* Newb.) Schniewind (1959) concluded that the difference is due primarily to the high radial tensile strength of the ray tissue.

FAILURE IN SHEAR

Côté and Hanna[1] found that when hardwoods are stressed parallel to the grain in shear there are similarities in the failures on radial and tangential surfaces. In species of high specific gravity the microfibrils of the thick S2 cell wall layer resist shear stresses due to their orientation, and intra-wall failures occur at the S1/S2 interface. For example, in figure 10-5 (top left) fragments of the S1 layer with more-or-less horizontal orientation are torn away from the S2 which has fibrillar orientation of 20 to 30° from axial.

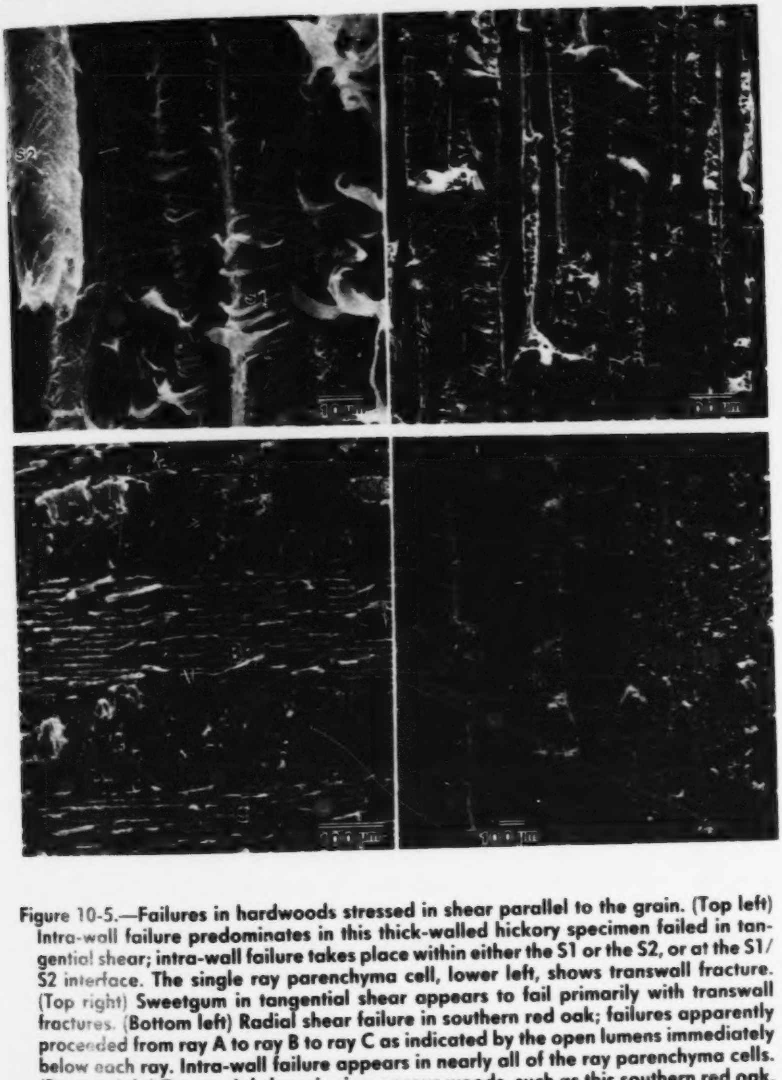

Figure 10-5.—Failures in hardwoods stressed in shear parallel to the grain. (Top left) Intra-wall failure predominates in this thick-walled hickory specimen failed in tangential shear; intra-wall failure takes place within either the S1 or the S2, or at the S1/S2 interface. The single ray parenchyma cell, lower left, shows transwall fracture. (Top right) Sweetgum in tangential shear appears to fail primarily with transwall fractures. (Bottom left) Radial shear failure in southern red oak; failures apparently proceeded from ray A to ray B to ray C as indicated by the open lumens immediately below each ray. Intra-wall failure appears in nearly all of the ray parenchyma cells. (Bottom right) Tangential shear in ring-porous woods, such as this southern red oak, tends to fail in earlywood where large, thin-walled vessels are concentrated. (Scanning electron micrographs from Côté and Hanna[1].)

In species with lower specific gravity the S2 layer is thinner and failures tend to be transwall (fig. 10-5 top right). Where there are fibers, intra-wall failure can be observed, however.

When viewed at macroscopic level, fracture planes are seen to pass through zones of least resistance. In radial shear, this zone of weakness is through the rays. In figure 10-5 (bottom left) the fracture proceeded in steps from the plane of ray A to that of ray B and then to ray C. Vessel elements did not appear to have a significant role due to weakness in the plane of the rays.

In tangential shear specimens there is a distinct plane of weakness in the earlywood region of ring-porous woods; failure is transwall through the vessel elements (fig. 10-5 bottom left), and the ray cells, offering little resistance, pull out in pieces. The fibers show intra-wall failures (Côté and Hanna[1]).

The Proceedings of the First International Conference on Wood Fracture (Barratt and Foschi 1979) provides additional data on fracture mechanics for readers desiring to delve more deeply into the subject.

SPECIFIC GRAVITY

Markwardt and Wilson (1935) observed that the specific gravity of wood is a measure of its content of wood substance, and is therefore positively correlated with its mechanical properties. The relationships they reported are of the form:

$$P = K(G)^n \tag{10-1}$$

Where:

P = property of interest
K = a constant, different for each property
G = specific gravity
n = an experimental constant, different for each property

By selection of the proper proportionality constant, K, and exponent, n, equation 10-1 can be fitted to data regardless of wood species. The fit of such generalized equations (table 10-1) is not as close as equations of the same form empirically derived for a single species. This is partially explained by the variation in cellular arrangement and chemical constituents among species—particularly variation in extractive content which can act as a bulking agent affecting strength and stiffness in compression and shear.

Data specific to certain properties of white ash and yellow-poplar (table 10-2) illustrate that individual species may have specific gravity—property relationships considerably different from the generalized equations of table 10-1

TABLE 10-1.—*Equations relating 13 mechanical properties to specific gravity (G) of green and air-dry, clear straight-grained wood of any species.* (Data from U.S. Department of Agriculture, Forest Service 1974)

		Equations[1]	
Property	Units	Green wood	Air-dry (12 percent moisture content)
Static bending:			
Fiber stress at proportional limit	psi	$10{,}200G^{1.25}$	$16{,}700G^{1.25}$
Modulus of elasticity	million psi	$2.36G$	$2.80G$
Modulus of rupture	psi	$17{,}600G^{1.25}$	$25{,}700G^{1.25}$
Work to maximum load	in-lb per cu in	$35.6G^{1.75}$	$32.4G^{1.75}$
Total work	in-lb per cu in	$103G^{2}$	$72.7G^{2}$
Impact bending, height of drop causing complete failure	in	$114G^{1.75}$	$94.6G^{1.75}$
Compression parallel to grain:			
Fiber stress at proportional limit	psi	$5{,}250G$	$8{,}750G$
Modulus of elasticity	million psi	$2.91G$	$3.38G$
Maximum crushing strength	psi	$6{,}730G$	$12{,}200G$
Compression perpendicular to grain, fiber stress at proportional limit	psi	$3{,}000G^{2.25}$	$4{,}630G^{2.25}$
Hardness:			
End	lb	$3{,}740G^{2.25}$	$4{,}800G^{2.25}$
Side	lb	$3{,}420G^{2.25}$	$3{,}770G^{2.25}$

[1] The properties and values should be read as equations; for example: modulus of rupture for green wood = $17{,}600G^{1.25}$, where G represents the specific gravity of ovendry wood, based on the volume at the moisture condition indicated.

TABLE 10-2.—*Equations relating selected mechanical properties of clear, straight-grained white ash and yellow-poplar to specific gravity*

Property	Equations[1]	
	Green wood	Wood at about 12% MC
WHITE ASH[2]		
Modulus of rupture (psi)	$24{,}000G^{1.5}$	$869 + 20{,}539G$
Fiber stress at proportional limit in bending (psi)	—	$4{,}167 + 5{,}645G$
Modulus of elasticity (thousand psi)	—	$489 + 1{,}834G$
Maximum crushing strength parallel to grain (psi)	—	$-121 + 10{,}330G$
Fiber stress at proportional limit in compression parallel to grain (psi)	—	$-729 + 3{,}617G$
Maximum shearing strength (psi)	—	$-283 + 3{,}184G$
Side hardness (pounds)	$-540 + 2{,}503G$	$-2{,}062 + 5{,}424G$
Toughness (inch-pounds)	—	$-58 + 254G$
YELLOW-POPLAR[3]		
Modulus of rupture (psi)	—	$37{,}000G^{1.5}$
Modulus of elasticity (thousand psi)	—	$4{,}400G^{1.25}$
Work to maximum load in bending (inch pounds per cubic inch)	—	$91G^{2.5}$
Maximum crushing strength parallel to grain (psi)	—	$16{,}300G^{1.25}$
Fiber stress at proportional limit in compression parallel to grain (psi)	—	$4{,}900G^{2.5}$
Maximum shearing strength (psi)	—	$4{,}500G^{1.5}$
Side hardness (pounds)	—	$5{,}000G^{2.5}$
Toughness (inch-pounds)	—	$1{,}020G^{3}$

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[1] The properties and values should be read as equations; for example: modulus of rupture for green white ash wood = $24{,}000G^{1.5}$, where G represents the specific gravity of ovendry wood, based on the volume at the moisture condition indicated.

[2] The equation for modulus of rupture of white ash when green is from Marquardt and Wilson (1935, p. 39); the other equations, which are of straight-line form over a limited range of G (0.55 – 0.96), are from Kraemer (1956), and describe wood taken from butt logs of five trees in each of eight Midwest locations.

[3] These equations from Luxford and Wood (1953) are based on lumber sampled at seven sawmills in the southern Appalachian Region.

Stern (1944b) provided additional data on yellow-poplar by correlating wood specific gravity with mechanical properties of wood sampled from a single 12-foot-long log 27 inches in diameter cut on the limestone formations of Clinch Mountain in Tazewell County, southwest Virginia. Over a range in specific gravity from about 0.39 to 0.49 (basis of ovendry volume and weight), the relationships were approximated by straight line functions in which the percentage increase in mechanical property, for each one-percent increase in specific gravity was as follows; wood at test averaged 8.75-percent moisture content:

Type of test	Stress at proportional limit	Ultimate stress	Modulus of elasticity
		Percent	
Static bending	0.00	0.39	0.83
Tension parallel to the grain	.23	.73	.65
Compression parallel to the grain	1.05	.06	.83
Toughness	—	.85	—
Shear parallel to the grain	—	1.60	—

Data summarized in table 9-15 failed to show a significant correlation (r = 0.19) between static modulus of elasticity of wood from 22 hardwood species and wood specific gravity. The specimens, which were tested at about 9.3 percent moisture content, were not clear or particularly straight-grained, but were typical of wood cut from 6-inch hardwoods growing on southern pine sites.

Wengert (1979) correlated average values of published toughness data of 17 eastern hardwoods with specific gravity; his regression equation (fig. 10-6) accounted for 94 percent of the variation in toughness at 12 percent moisture content.

10-2 EFFECT OF PRIOR-TO-SERVICE HISTORY

Mechanical properties of wood as it comes from the tree can be improved or impaired by treatments received prior to its ultimate service. For some uses, e.g., hardwood pallet deckboards, it is usual to utilize freshly sawn lumber undried and in its natural state. For some applications under adverse conditions, however, wood may require treatment at high temperature, chemical modification, and impregnation with preservations. Some classes of structural flakeboard or fiberboard might fall into this latter category. Brief discussions of factors that can modify properties follow. Where data specific to the hardwoods under study are not published, sources of more general information are cited. The effect of form (natural round cross section versus sawn square or rectangular cross section) on mechanical properties of posts is shown in table 22-26; in brief, round posts have greater strength, stiffness, and energy-absorbing properties than corresponding sawed posts (Doyle 1969).

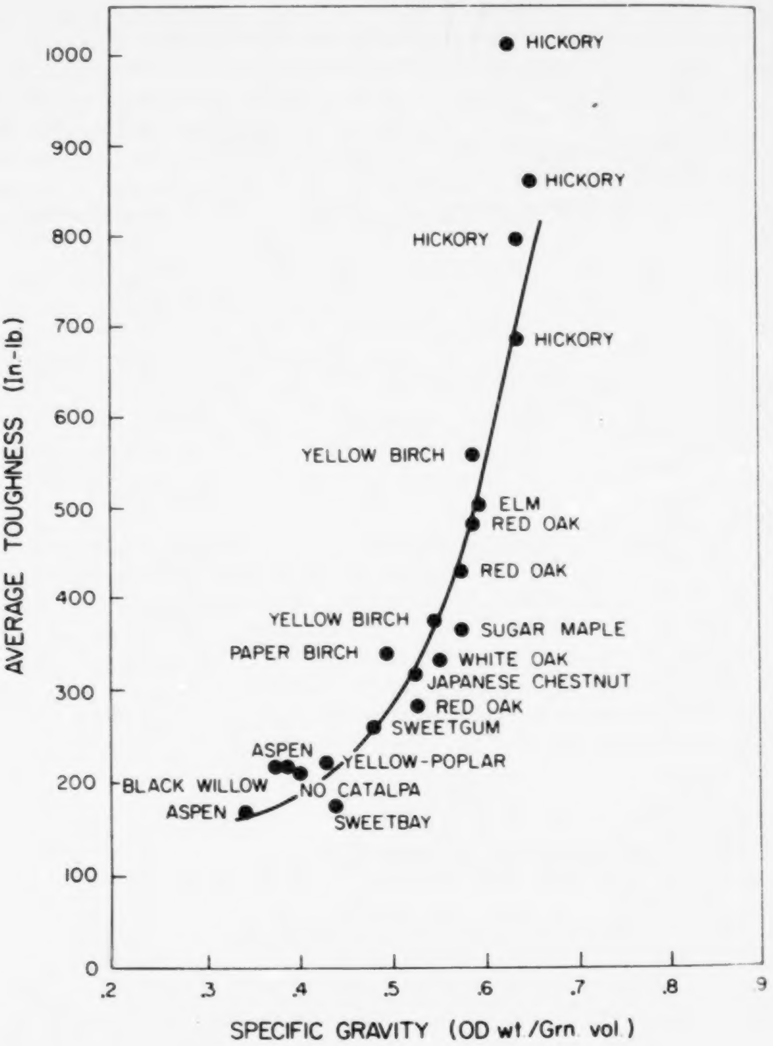

Figure 10-6.—Toughness of 17 species of eastern hardwoods at approximately 12 percent moisture content correlated with specific gravity (SG) based on ovendry weight and green volume. The solid line is a plot of the equation:

$$\text{Toughness, inch-pounds} = 151 + 8{,}072\,(SG)^6$$

(Drawing after Wengert 1979.)

INSECT AND WOODPECKER DAMAGE

Standing hardwoods—both living and dead, and lumber after it is cut, may be attacked by wood boring insects. The nature and severity of these attacks are described in chapter 11. Woodpeckers also make excavations in standing trees (see Koch 1972, pp. 720-730). Small bore holes and excavations do not greatly affect the modulus of elasticity of wood, but strength in compression, tension, and shear is reduced in proportion to the amount of wood removed in the plane of stress. Strength in bending is reduced in proportion to reduction of the moment of inertia of the most highly stressed cross-section (moment of inertia is a function of the net breadth of a section after deducting void spaces, and its depth).

STAIN AND DECAY

As noted in chapter 11, **mold** and **stain** fungi feed primarily on contents of cells and do not destroy cell walls. Resulting reductions in wood specific gravity and strength properties are therefore usually minor. Toughness and shock resistance, however, may be reduced by up to 30 percent (U.S. Forest Products Laboratory 1974). The occurrence and significance of discolored wood is further discussed in section 9-1.

Campbell (1959) found in tests on artificially inoculated sticks of sweetgum sapwood that stain fungi *Endoconidiophora virescens* Davids., *Diplodia natalensis* Evans, and *Ceratocystis pluriannulata* (Hedgc.) Moreau caused small but statistically significant reductions in modulus of rupture in 12 to 17 weeks. The largest reduction averaged 5.2 percent. Only C. *pluriannulata* caused a statistically significant reduction (15 percent) in work to maximum load, although reductions amounting to 6 to 10 percent were indicated for most of the other cases.

Decay fungi destroy cell wall structure, significantly reduce specific gravity, and seriously reduce strength. Even apparently sound wood adjacent to obviously decayed parts may contain early stages of decay that significantly weaken it, especially in shock resistance. Wood that must serve where strength is important should contain no decay, with the possible exception of that clearly localized in knots.

Toole (1971) correlated dry weight loss from white-and brown-rot decay fungi to percent diminution in radial compressive stress in small blocks of sweetgum, hackberry and southern pine when loaded to 5-percent strain. He found that strength diminution was substantial in all species, but less in the hardwoods than in southern pine. At 25-percent weight loss, radial compression strength in southern pine was diminished by about 90 percent while sweetgum and hackberry had diminution of about 55 percent. For the seven decay fungi tested, average percent reduction in stress at five percent compression in the radial direction (Y) was correlated with percent dry weight loss (X) as follows for sweetgum and hackberry ($R^2 = 0.93$):

$$Y = 0.74 + 4.45X - .07X^2 \tag{10-2}$$

SEASONING DEGRADE

During air or kiln drying, hardwood products may develop splits, checks, or collapse (see section 8-4) that reduce their strength in comparison to wood of equal moisture content but dried defect-free. For example, a split which surfaces on one edge of a joist will reduce its bending strength, or a central radial check in a flat-sawn joist may cause it to fail in horizontal shear along the check. Table 22-26 contains quantitative data relating strength of oak and hickory posts when green and air dry.

EXPOSURE TO HIGH TEMPERATURE

When wood is exposed to temperatures in excess of 150°F for extended periods, it will suffer a permanent loss of strength related to the temperature, time, and exposure medium. Such exposure degrades wood substance, which results in loss of weight and strength. Hardwoods are more adversely affected by exposure to elevated temperatures than softwoods.

Millett and Gerhards (1972) found that wood from red oak species oven-heated at 0-percent moisture content for periods up to 255 days, cooled to near 75°F, and conditioned to 7- to 12-percent moisture content before test, had significantly diminished modulus of rupture (fig. 10-7A); modulus of elasticity at first increased, but on continued exposure was also diminished (fig. 10-7B). Specimens measured 1/4-inch tangentially, 1/2-inch radially, and 6-1/2 inches in length.

Davis and Thompson (1964) observed that 12-inch-long 5/8-inch-square specimens of wood of red oak species were significantly reduced in toughness (fig. 10-7C) and hemicellulose content when ovendried for only an hour at temperatures from 150° to 200°C.

Tensile properties perpendicular to the grain of small northern red oak specimens (1/2 x 1/2 inch at test section) evaluated at 80°F were also found substantially reduced by 30 days exposure in air at 180°F as follows (Youngs 1957):

Moisture content and property	Percent reduction
12-percent	
Modulus of elasticity	10
Maximum stress	22
Green	
Modulus of elasticity	50
Maximum stress	70

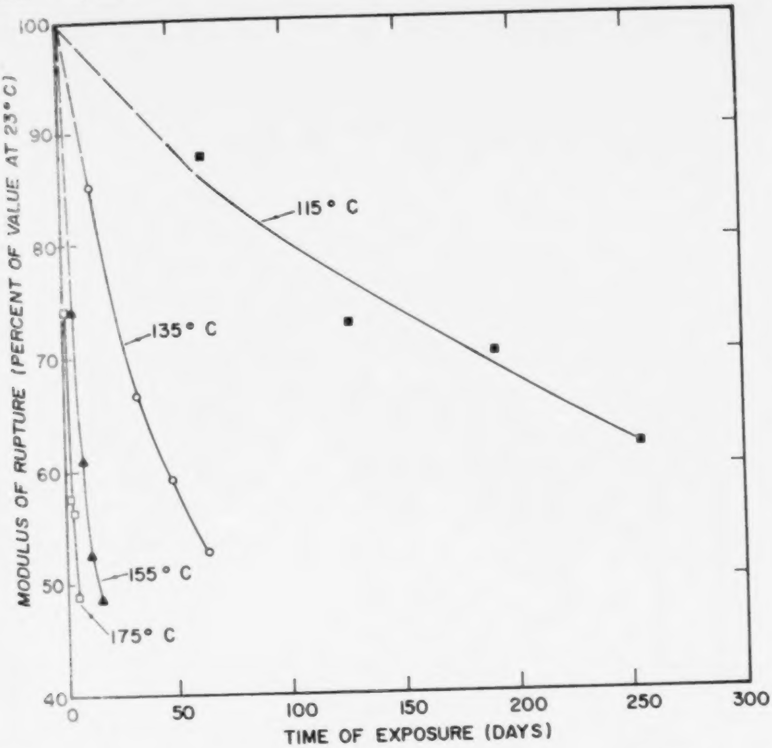

Figure 10-7A.—Permanent effect of oven heating at four temperatures on the modulus of rupture of wood of red oak species. (Data from Millett and Gerhards 1972.)

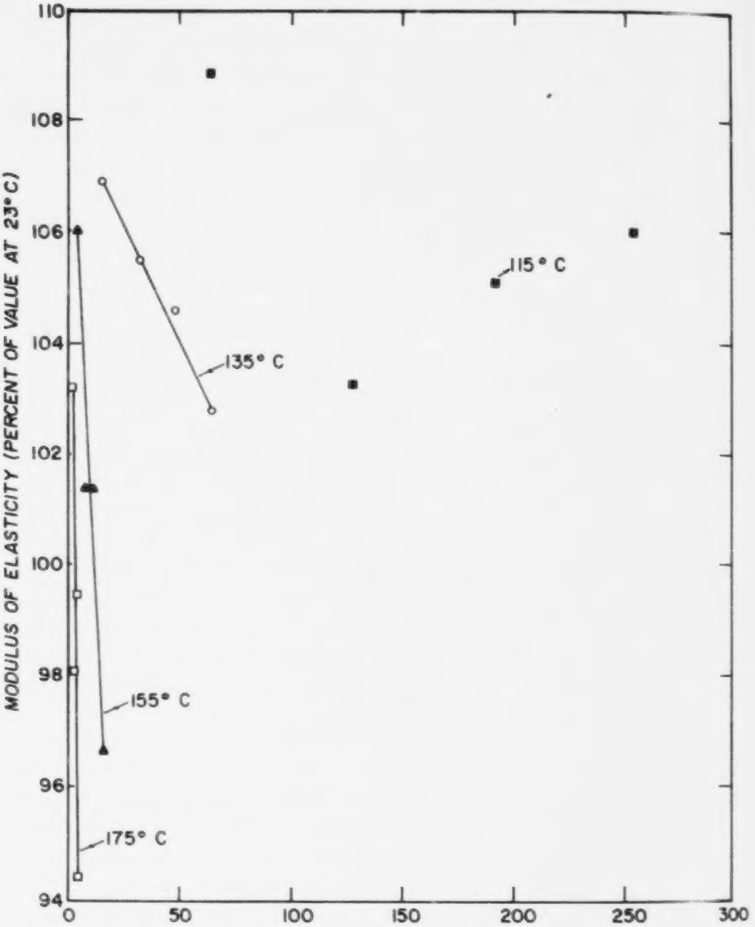

Figure 10-7B.—Permanent effect of oven heating at four temperatures on the modulus of elasticity of wood of red oak species. (Data from Millett and Gerhards 1972.)

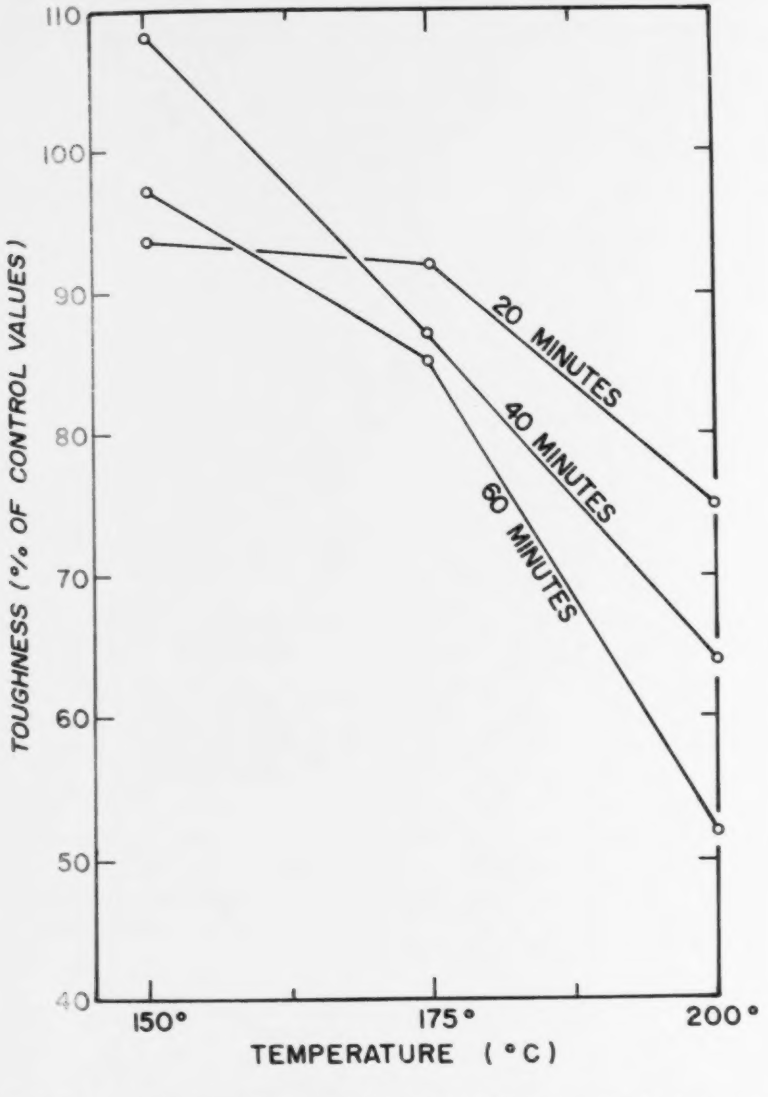

Figure 10-7C.—Relationship between toughness of dry 5/8-inch-square red oaks specimens and temperature in the oven in which they were heated for three periods. (Drawing after Davis and Thompson 1964.)

Pillow (1929), in a study of air-dried white ash specimens 5/8-inch square heated for periods up to 8 days at 220° and 280°F drew the following conclusions:

- Temperatures as high as 220°F maintained for eight days, or 280°F, maintained for one day, did not cause white ash wood to have a brash failure. A temperature of 280°F maintained for more than one day, however, resulted in failures that became progressively more brash (fig. 10-7D).
- Toughness was reduced by heat treatments at temperatures of 220° and 280°F, maintained for periods up to eight days (fig. 10-8), whereas end-crushing strength was not seriously affected.
- Specific gravity of dry white ash was only slightly reduced by a temperature of 220°F maintained for eight days, but eight days at 280°F reduced specific gravity by 7 percent (fig. 10-8).
- The moisture-holding capacity of white ash at a moisture content in equilibrium with relative humidities of 30, 60, and 90 percent was reduced by temperatures of 220° and 280°F, maintained for periods of one to eight days (fig. 10-8).
- Temperatures of 220°F to 280°F, when applied for one to eight days, progressively darkened wood of white ash from a cream color to coffee brown at the most severe treatment.
- Any brashness occurring in normal-colored white ash is due to some cause other than exposure to high temperatures.

In this experiment, the specimens were surrounded by dry sand and sealed in steel pipe sections; these pipe sections were then placed in a steam retort held at 220° or 280°F. At the 280°F temperature, the pipe containers allowed some steam to enter; this exposure to steam probably accelerated degradation.

Heating wood in water diminishes its modulus of rupture and work to maximum load more quickly than if heated in air at the same elevated temperatures; exposure to steam degrades wood more rapidly than exposure to hot water. Curves of these relationships have not been established for hardwoods; data for softwoods, however, can be found in the Wood Handbook (U.S. Department of Agriculture, Forest Service 1974, p. 4-36).

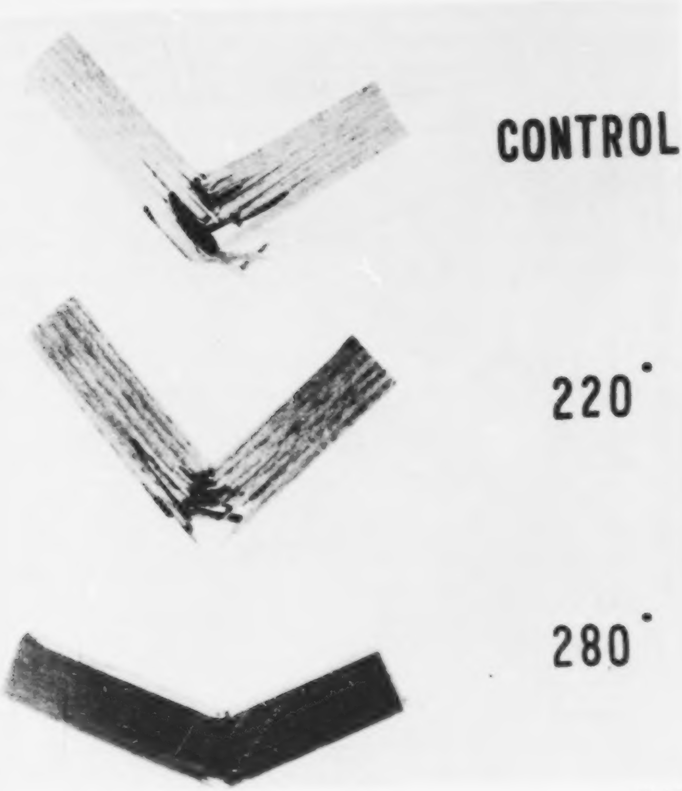

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Figure 10-7D.—White ash toughness specimens initially air dried and then broken following no heat treatment (control) and after heating for eight days at 220° and 280°F. The 280°F treatment caused significant loss of toughness as indicated by the resulting brash failure mode. (Photo from Pillow 1929.)

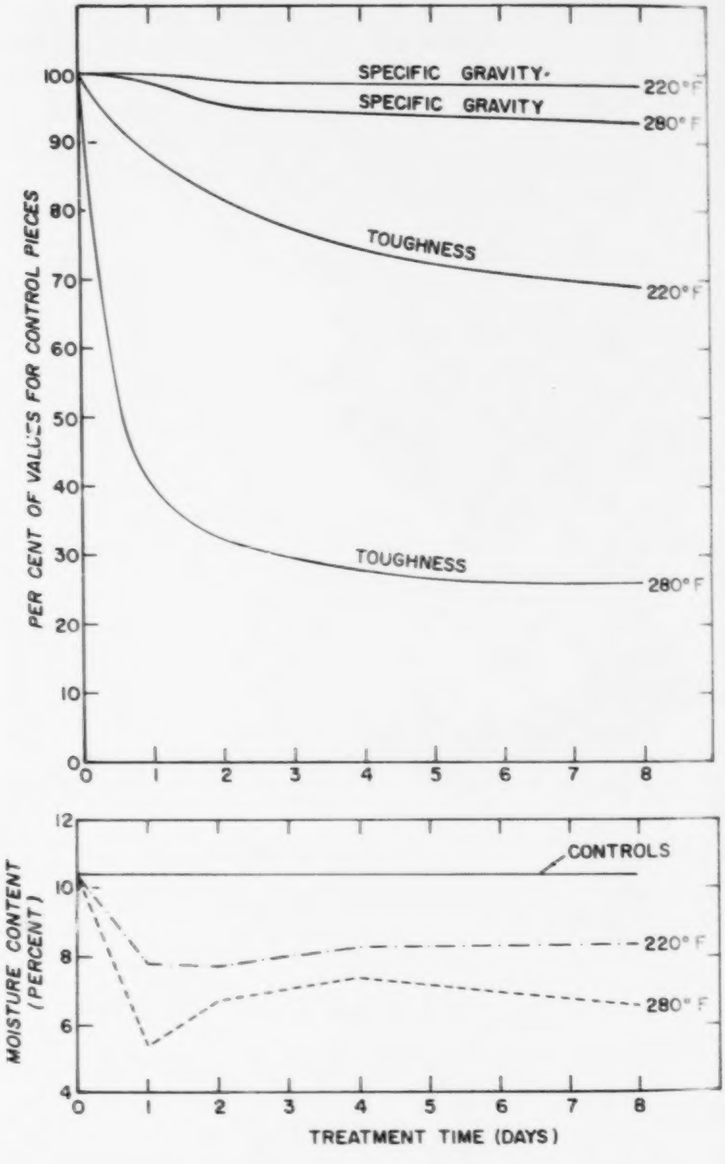

Figure 10-8.—(Top) Relationship between duration of heating, toughness, and specific gravity of previously air-dried white ash specimens 5/8-inch square measuring 10 inches along the grain. (Bottom) Moisture contents of air-dried white ash controls and matched specimens heated for eight days at 220° and 280°F and then equilibrated at 65-percent relative humidity and 90°F. (Drawing after Pillow 1929.)

Davis and Thompson (1964) steamed 5/8-inch square specimens of red oak species at 126° to 148°C for periods up to two hours and found that specimens retained only about 60-percent of original toughness after the most severe treatment (fig. 10-9).

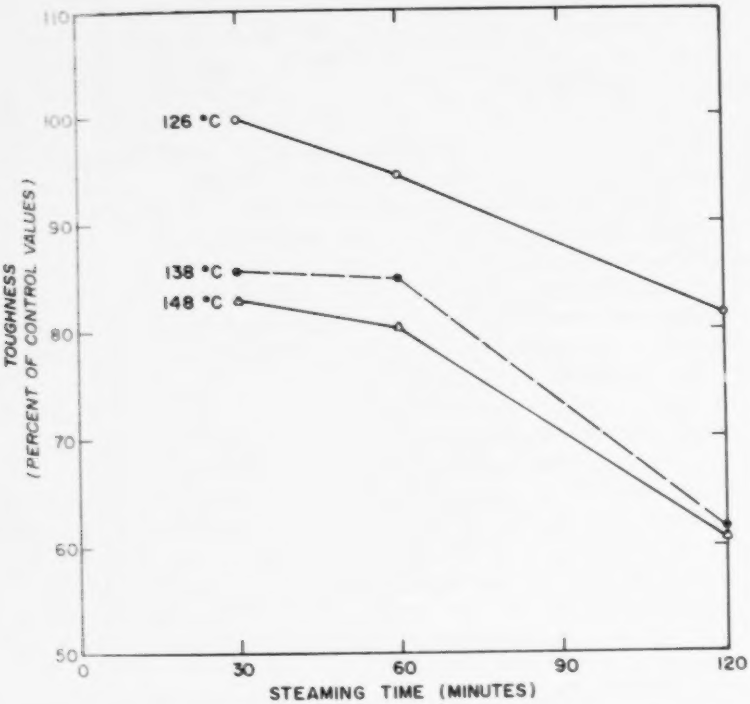

Figure 10-9.—Relationship between toughness of wood of red oak species and time of exposure to steam at three temperatures. (Drawing after Davis and Thompson 1964.)

Kubinsky's (1971) experiments steaming 20 mm cubes of green northern red oak at atmospheric pressure for 6 and 96 hours resulted in diminished (20 to 55 percent) fiber stress at proportional limit in transverse compression (steamed and unsteamed wood both tested at initial high moisture content); this strength property was restored, however, after air drying the wood (steamed and unsteamed wood both tested at 10-percent moisture content). Lumen diameters in fibers were significantly reduced by steaming and the warty layer was disrupted (fig. 8-29). The almost full recovery of original strength on air drying was presumed to result from internal shrinkage which restored disrupted tissue.

See section 21-5 (tables 21-21 through 21-23 and related discussion) for additional information on the effects of temperature on mechanical properties of wood.

Fibers may also be weakened by immersion in hot water or steam. No data are available on southern hardwoods, but gently delignified, hemicellulose-free, southern pine pulp heated in water at temperatures (and times) typical of kraft pulp cooks yielded handsheets with 20 percent less tensile strength, 30 percent less burst strength, and 45 percent less tear strength than matched pulp not subjected to cooking temperatures (Atalla 1977).

NUCLEAR RADIATION

Very large doses of gamma rays or neutrons can cause substantial degradation of wood. Such degradation is illustrated by the observations of Tabirih et al. (1977), who exposed white oak heartwood cubes measuring 1 cm on each side to 650, 950, and 1,900 megarads[3] of cobalt-60 gamma radiation. They found that the holocellulose portion of the cell walls was degraded while the lignin percentage remained relatively unchanged. Tangential vessel diameter, ray cell length, and length and width of intervessel pits increased upon exposure while tangential vessel-wall thickness, ray cell double-wall thickness, and latewood fiber double-wall thickness decreased.

In general, irradiation with gamma rays in doses up to about 1 megarad has little effect on the strength properties of wood. As dosage increases above 1 megarad, tensile strength parallel to grain and toughness decrease. At a dosage of 300 megarads, tensile strength is reduced about 90 percent. Gamma rays also affect compressive strength parallel to grain above 1 megarad, but strength losses with further dosage are less than for tensile strength. Only about one-third of the compressive strength is lost when the total dose is 300 megarads. Effects of gamma rays on bending and shear strength are intermediate between the effects on tensile and compressive strength (U.S. Forest Products Laboratory 1974).

Tests of wood excised from 200 American elm trees irradiated while growing and wood from a non-irradiated control group of 200 trees about 2 miles away indicated that gamma radiation dose levels of 15,000, 22,000 and 30,500 roentgens[4] significantly increased modulus of elasticity and decreased maximum work to fracture in static bending (Shuler et al. 1975).

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[3] A rad is a measure of absorbed dose (in any medium), i.e., 100 ergs per gram.

[4] A roentgen is also a measure of absorbed dose, but in soft tissue, i.e., 83 to 93 ergs per gram.

IMPREGNATION FOR PRESERVATION

Non-swelling liquids such as creosote or the petroleum oils used to carry some preservatives have no appreciable effect on mechanical properties of wood (U.S. Department of Agriculture, Forest Service 1974). Walters' (1967) study of sweetgum heartwood—a wood difficult to impregnate—provides supporting data over a range of treating temperatures and pressures. Table 22-26 contains data comparing mechanical properties of untreated oak and hickory highway posts to those of posts pressure treated with creosote; table 21-23 compares strength of untreated and creosoted oak and gum crossties.

Treating solutions of most salt-type preservative formulations contain at least one salt that readily hydrolyzes to form a mineral acid; such salts are potentially capable of degrading wood. The degree of degradation varies among species. Thompson (1964) found that toughness of sweetgum and yellow-poplar veneer was not significantly reduced by impregnation with Celcure, Chemonite, Boliden Salt, and copper chromate. Black tupelo veneer treated with these four preservatives, however, averaged 36, 24, 17, and 5 percent less in toughness (respectively) than untreated controls. Finnorn and Holcombe (1959) have defined permissable bending radii for three thicknesses of Tanalith-treated black tupelo and hickory.

Even low concentrations of acidic salts may migrate to the surface of railroad ties that are occasionally wetted and dried in a hot, arid region. This migration, combined with the high concentrations of salt relative to the small amount of water present, causes an acidic condition sufficient to make wood brittle (U.S. Department of Agriculture, Forest Service 1974).

See section 21-5 for additional information on the effects of preservative treatments on wood properties.

Impregnation of hardwoods with some fire-retardant salts, in combination with heat of the treatment and kiln drying subsequent to treatment, may reduce modulus of rupture by as much as 20 percent, while work to maximum load and toughness may be reduced up to 45 percent. Stiffness is not appreciably affected by fire retardant treatment (U.S. Department of Agriculture, Forest Service 1974).

See table 21-26 and related discussion for further information on the effects of fire-retardant chemicals on mechanical properties of wood.

CHEMICAL MODIFICATION

Mechanical properties and dimensional stability may be modified by applications of heat and pressure, impregnation with plastics or chemical reagents, and exposure to radiation. A review of most of these processes can be found in Koch (1972, pp. 1128-1143). More recent literature on treatments providing a degree of dimensional stability is listed at the conclusion of section 8-4 in this text; see also figure 21-12 and related discussion. Treatment of red maple and sweetgum with vinyl monomers to increase compressive strength is described by Young and Meyer (1968). Loos and Kent (1968) achieved a two-thirds increase in the shear strength of yellow-poplar by impregnating it with methyl methacrylate. Increase in stability and in some strength properties of northern red oak (but not in modulus of rupture or modulus of elasticity) were accomplished through acetylation (Dreher et al. 1964).

10-3 EFFECT OF CONDITIONS DURING SERVICE

Wood is an outstanding structural material because of its high strength/weight ratio, easy workability, ready availability in a range of dimensions, low thermal and electrical conductivity, economy, and its ability to serve well under a wide range of conditions. Under some adverse conditions, however, the mechanical properties of wood are impaired. This section discusses data relating mechanical properties of southern hardwoods to service conditions of moisture content, temperature, rate of loading, duration of loading, and chemical contaminants. Attack on wood by plant organisms and insects is discussed in section 10-2 and chapter 11. Readers desiring a comprehensive overview of the structural use of wood of all species in adverse environments are referred to Meyer and Kellogg (1982).

MOISTURE CONTENT

In rain-sheltered service above ground, wood may attain equilibrium at moisture contents from near ovendry to over 20 percent (table 8-6). If rain wetted or submerged in water, moisture contents in service can exceed 30 percent (dry-weight basis), reaching maximums of 40 to 140 percent depending on species (table 8-1). Because of this wide range in moisture content of wood in service, the relationship between moisture content and mechanical properties is of great practical significance.

With the exception of impact bending, work to maximum load, and tension properties perpendicular to the grain—which often vary with species and are erratic in response to moisture content change—wood weakens as its moisture content is increased from ovendry to approximately fiber saturation. Above this experimentally determined interaction point (M_p), changes in mechanical properties are minimal (Wilson 1932). The U.S. Department of Agriculture, Forest Service (1974, p. 4-32) expressed the relationship describing clear-wood property changes at about 70°F as follows:

$$P = P_{12}\left(\frac{P_{12}}{P_g}\right)^{-\left(\frac{M-12}{M_p-12}\right)} \qquad (10\text{-}3)$$

where:

P is the property

M is the percent moisture content for which P is desired

P_{12} and P_g are the property values at 12-percent moisture content and when green (from table 10-2)

M_p has been determined as 24 percent for white ash; for other pine-site hardwoods M_p is commonly considered to be 25 percent (U.S. Department of Agriculture, Forest Service 1974, p. 4-32).

Equation 10-3 can be used to estimate a property at any moisture content below M_p from the species data given. For example, suppose the modulus of rupture of clear white ash at 8-percent moisture content (with no drying defects) is wanted. Using information from table 10-2:

$$P_8 = 15{,}400\left(\frac{15{,}400}{9{,}600}\right)^{-\left(\frac{-4}{12}\right)} = 18{,}028 \text{ psi} \qquad (10\text{-}4)$$

If moisture content exceeds M_p, the green wood values in table 10-2 apply.

The diminution of strength with increasing moisture content described by equation 10-3 is separate from, and is additive to, strength diminution from decay which is fostered by high moisture content.

Readers interested in the immediate effects of moisture content and temperature on the mechanical properties of woods of all species should read Gerhards' (1982) review of the subject. A few data specific to southern hardwoods follow.

Bending strength.—Commercial sizes and grades of dry lumber that have been soaked in water to above M_p may vary somewhat in ratios of dry strength to green strength from those indicated in tables 10-1, 10-2, and 10-6. Wolfe and Moody (1978) found that the reduction in load carrying capacity of laminated beams due to 4 months of water soaking was 15 percent for Douglas-fir and 19 percent for southern pine. The decrease in modulus of elasticity due to water soaking was 12 percent for Douglas-fir and 9 percent for southern pine. Test beams had 9 laminations, measured 3.13 inches wide, 12 inches deep, and 20 feet long, and had 12 to 13 percent moisture content before water soaking. Moisture content in the soaked Douglas-fir beams varied from 20 percent in the core to 80 percent in the shell; the southern pine beams were wetter, having 46-percent moisture content in cores and 90 percent in shells.

Laminated white oak beams 1.75 inches wide, 3.75 inches deep, and 45 inches long comprised of six 5/8-inch-thick essentially clear boards were tested in bending when at 11 to 12 percent moisture content; bending properties of these dry beams were compared with those of matched beams salt-water soaked for three months to a moisture content of about 40 percent and tested wet. The decrease in modulus of elasticity after salt-water soaking averaged about 26 percent; modulus of rupture decreased about 41 percent (Freas and Werren 1959).

Szabo and Ifju (1970), in tests of small clear yellow-poplar beams 3/8-inch wide by 1/2-inch deep by 32 inches long, found that rate of **creep** (non-elastic deformation) under constant load was highest during moisture adsorption and desorption; creep during adsorption was greater than during desorption.

Tension and compression properties perpendicular to the grain.—Youngs (1957) found that when northern red oak was stressed perpendicular to the grain, both modulus of elasticity and maximum stress were negatively related to wood moisture content above 6 percent and to temperature differences from 80° to 180°F (fig. 10-10). Both values were higher under all test conditions when the perpendicular stress was applied at 90° to the growth rings than when applied parallel to them; this difference is probably attributable to the rays (Schniewind 1959). In Youngs' experiments stress relaxation and irrecoverable creep increased with increased moisture content.

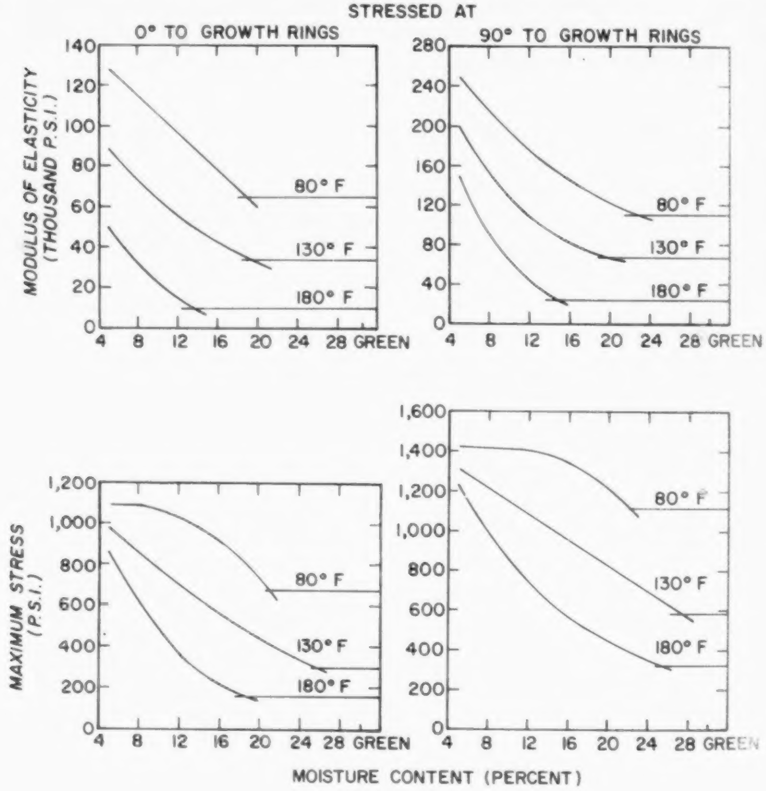

Figure 10-10.—Relationship of modulus of elasticity (top) and maximum stress (bottom) to moisture content and temperature in northern red oak when stressed perpendicular to the grain at 0 and 90 degrees to the growth rings. (Drawing after Youngs 1957.)

Modulus of rigidity.—Tang et al. (1971) noted that directional shear moduli of rigidity of wood are necessary elastic constants in the design of composite beams. Poles (and sometimes beams) exhibit uneven moisture distribution along their length—e.g., below-ground portions are wet and above-ground portions dry.

Mark et al. (1970) used the method described by the American Society for Testing and Materials (1967) to determine variation with moisture content of moduli of rigidity in the three major planes (G_{LT}, G_{LR}, and G_{RT}) of yellow-poplar wood plates cut from a 26-inch tree. The plates were designated LT, LR, and RT (i.e., cross-sectional plane), where L, R, and T correspond to the longitudinal, radial, and tangential directions. For example, G_{LR} is the modulus of rigidity based on shear strain in the LR plane and shear stresses in the LT and RT planes. Both sapwood and heartwood plates were prepared, but no significant differences in moduli of rigidity were observed between these wood types. Pooled results for G_{LT} yielded a value of about 55,000 psi in wood above fiber saturation point, increasing to approximately 85,000 psi at zero moisture content. G_{LR} was about 60,000 psi in saturated wood and 125,000 psi in dry wood. G_{RT} increased from about 10,000 psi in saturated wood to approximately 25,000 psi in dry wood (fig. 10-11).

Tang et al. (1971) determined modulus of rigidity values in wood cut from five scarlet oaks of large diameter. Values when green and dry were about as follows (fig. 10-12):

Statistic	4-Percent moisture content	Green
	Thousand psi	
G_{LT}	120	60
G_{LR}	160	75
G_{RT}	48	26

Flakeboard.—Southern hardwood phenolic-bonded flakeboards with 0.015-inch face flakes randomly oriented over 0.025-inch core flakes lose over 50-percent of most strength properties when serving in very humid atmospheres compared to boards in service at 50-percent relative humidity (fig. 10-13). The equilibrium moisture content (emc) of such flakeboard in varying humidities is shown in figure 8-18. The literature on the effects of humidity on softwood flakeboards and particleboards is voluminous; a sampling of the references includes the following:

Reference	Subject
Dinwoodie (1977)	Deterioration of chipboard under cyclic humidity conditions
Halligan and Schniewind (1972)...........	Effect of moisture on physical and creep properties of particleboard
Halligan and Schniewind (1974)...........	Prediction of particleboard mechanical properties at various moisture contents
Haygreen et al. (1975)...................	Flexural creep in particleboard under changing humidity conditions
McNatt (1974b)	Properties of particleboards at various humidity conditions
McNatt (1975b)	Humidity effects on properties of structural particleboards from forest residues

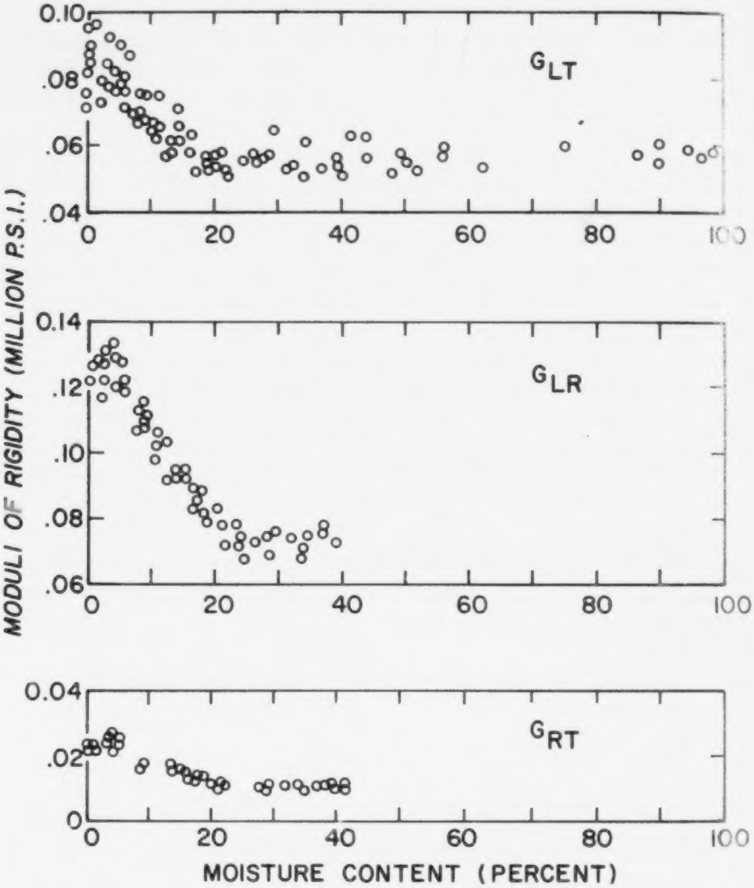

Figure 10-11.—Modulus of rigidity in yellow-poplar related to moisture content base on dry weight. G_{LT}, G_{LR}, and G_{RT} designate modulus of rigidity based on shear stra in the longitudinal-tangential, longitudinal-radial, and radial-tangential planes an shear stresses in the two planes not designated. (Drawings after Mark et al. 1970

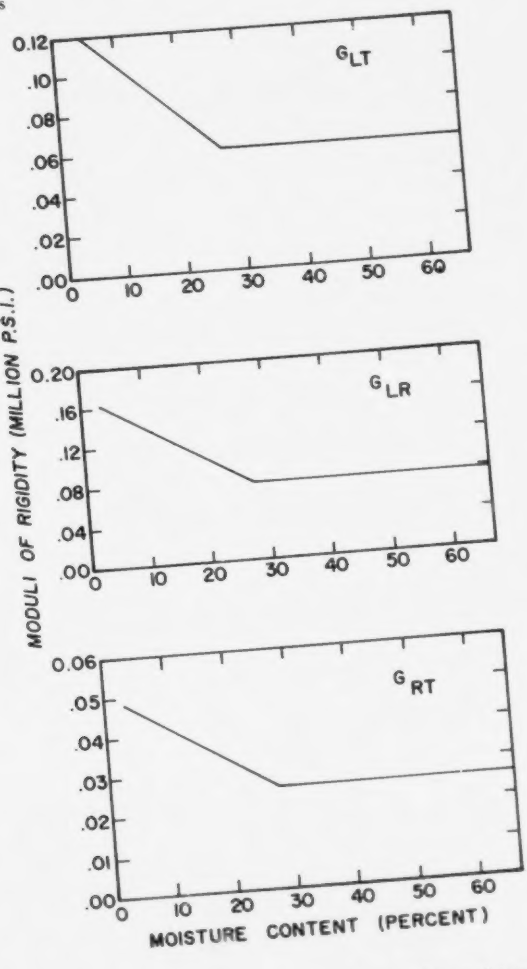

Figure 10-12.—Modulus of rigidity in scarlet oak related to moisture content based on dry weight. G_{LT}, G_{LR}, and G_{RT} designate modulus of rigidity based on shear strain in the longitudinal-tangential, longitudinal-radial, and radial-tangential planes and shear stresses in the two planes not designated. (Data after Tang et al. 1971.)

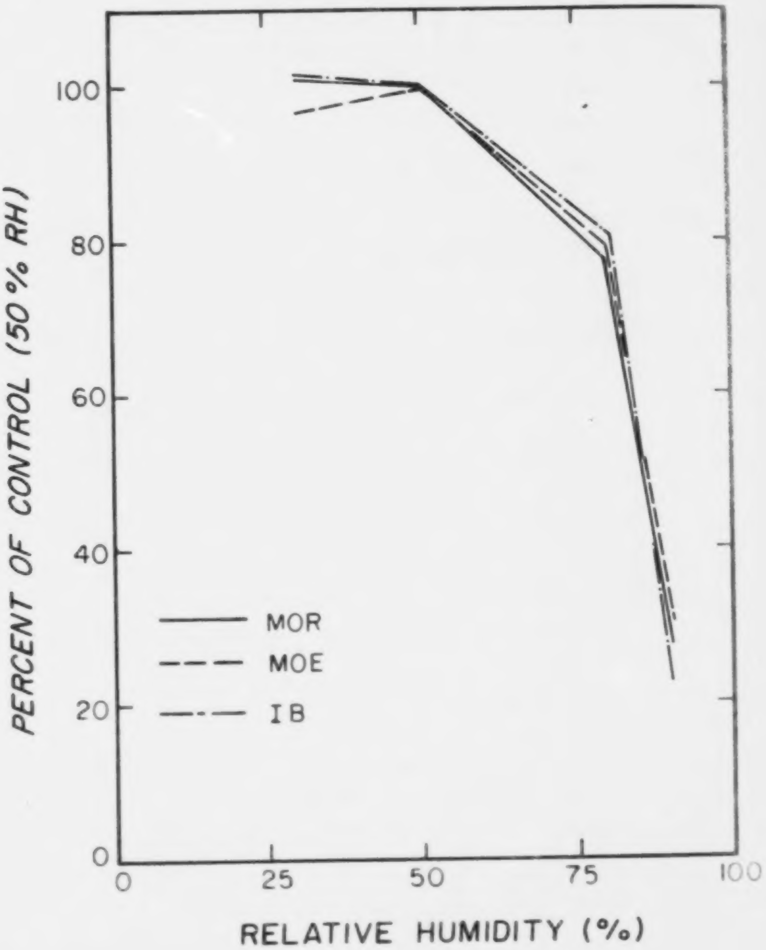

Figure 10-13.—Relative humidity in service related to three mechanical properties of phenolic-bonded flakeboard (comprised of equal weight portions of white oak, southern red oak, hickory, sweetgum, and southern pine) fabricated with 0. 015-inch thick face flakes and 0. 025-inch-thick core flakes both randomly oriented. Board density at 50-percent RH was 50 pounds per cubic foot. MOE and MOR were based on dimensions at test. (Drawing from files of E. W. Price.)

Fiberboard.—The emc of medium-density fiberboard and standard and oil-tempered hardboard is generally below 15 percent even in atmospheres of 80 to 90 percent relative humidity (see sect. 8-3 and figs 8-15 through 8-19). Strength and stiffness diminution of 4.8 mm hardboards serving in humidities of 90 to 100 percent is substantial, however (fig. 10-14). McNatt (1974a) found that most strength properties of 1/4-inch tempered hardboard conditioned at 90-percent relative humidity were 70 to 90 percent of those at 65-percent relative humidity; interlaminar shear modulus was affected more than any other property by changes in moisture content, its value in samples at equilibrium in 90-percent relative humidity being only 60 percent that of samples at equilibrium in 65-percent. Sauer and Haygreen (1968) found that the flexural creep behavior of wet- and dry-process hardboard was greatly influenced by water sorption. Adsorption produced far greater creep than desorption or constant conditions. Dry-process hardboard exhibited greater creep than wet-process hardboard except under test conditions of low stress and moisture content.

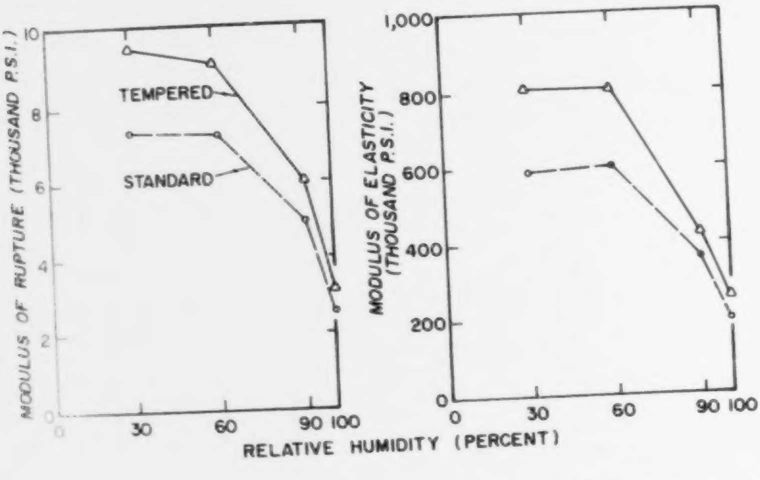

Figure 10-14.—Modulus of rupture (left) and elasticity (right) of 4. 8 mm hardboards related to relative humidity of the air in which they serve. (Drawing after Princes Risborough Laboratory 1975.)

TEMPERATURE

Solid wood.—Wood tends to weaken with increasing temperature and to become stronger when temperature is lowered. The effect is immediate (fig. 10-15).

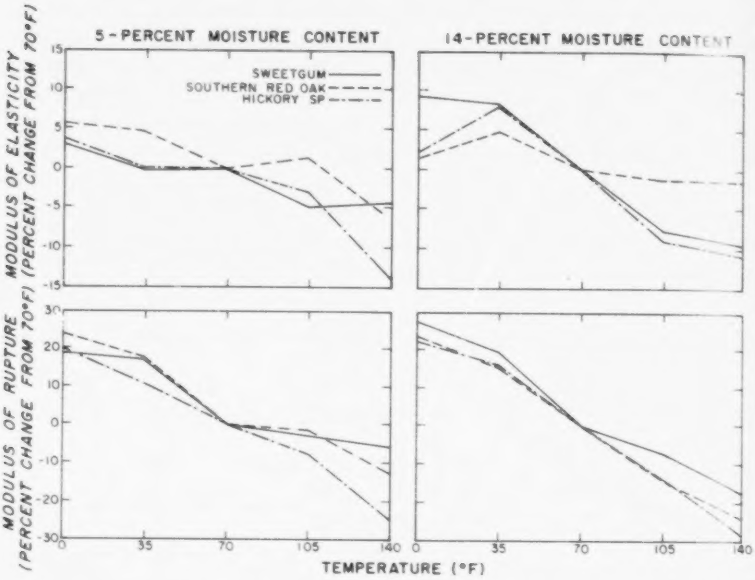

Figure 10-15.—Immediate effect of temperature variation from 70°F on modulus of elasticity and modulus of rupture of clear wood of three southern hardwoods at two moisture contents. Specimens measured 1/2-inch square and were tested by center-point loading over a 10-inch span. Each point represents an average of 15 specimens conditioned for 15 minutes at the designated temperature prior to evaluation. (Data from: Price, E. W. 1980. Immediate effect of temperature on mechanical properties of three southern hardwoods. Study FS-SO-3201-6, USDA Forest Service, Southern Forest Experiment Station, Alexandria, La.)

Youngs (1957, figs. 8 and 9) found the following immediate reductions in tensile properties perpendicular to the grain of northern red oak tested at 130° and 180°F compared to 80°F; specimens were 1/2-inch square at the test section:

Moisture content and property	130°F	180°F
	Percent reduction	
12-percent		
Modulus of elasticity	50	80
Maximum stress	15	65
Green		
Modulus of elasticity	52	83
Maximum stress	58	75

Young's data show the interrelationship of temperature and moisture content (fig. 10-10).

In general, temperature and moisture effects may be offsetting in their combined influence on mechanical properties of solid wood, because moisture is generally lost as temperature is increased. For a review of the literature see Gerhards (1982).

Fiberboard.—In tests of two brands of 4.8-mm-thick oil-tempered hardboard and two brands of standard hardboard of the same thickness, the Princes Risborough Laboratory (1975) observed that boards conditioned and tested at 40° and 65-percent relative humidity had significantly lower moduli of rupture and elasticity than matched specimens conditioned to the same moisture content but at 25°C (60-percent relative humidity), as follows:

Property and hardboard type	Diminution of property at 40°C
	Percent
Modulus of rupture	
Oil-tempered	21
Standard	14
Modulus of elasticity	
Oil-tempered	11
Standard	4

Flakeboard.—No data are published on temperature-related diminution of strength of flakeboards made from southern hardwoods.

DURATION OF STRESS AND RATE OF STRAIN

The length of time a load acts on a wood member is negatively correlated with the load it can safely carry. A wood member continuously loaded for 10 years can carry only 50 to 80 percent of the load required to produce failure during a standard strength test of a few minutes duration. Conversely, when a load is applied to a member in 1 second, its load-carrying capacity to rupture is increased 10 to 30 percent over that indicated by standard strength tests (Gerhards 1977, p. 17). For simplicity and ease of understanding, figure 10-16 illustrates the concept with a single line. The relationship varies, however, wtih mechanical property and among species.

Thus wood structural elements designed to accommodate prolonged loads have a built-in safety factor that allows them to resist without failure the overloads from short-time loading conditions such as snow, wind, earthquake, or blast.

Readers desiring to study the subject in greater depth will find reviews by Barrett (1982), Gerhards (1977), McNatt (1970, 1975a), McNatt and Werren (1976), and Ugolev (1976) useful. Data describing creep characteristics of flakeboards made from southern hardwoods can be found in figures 24-46ABCDE and related discussion.

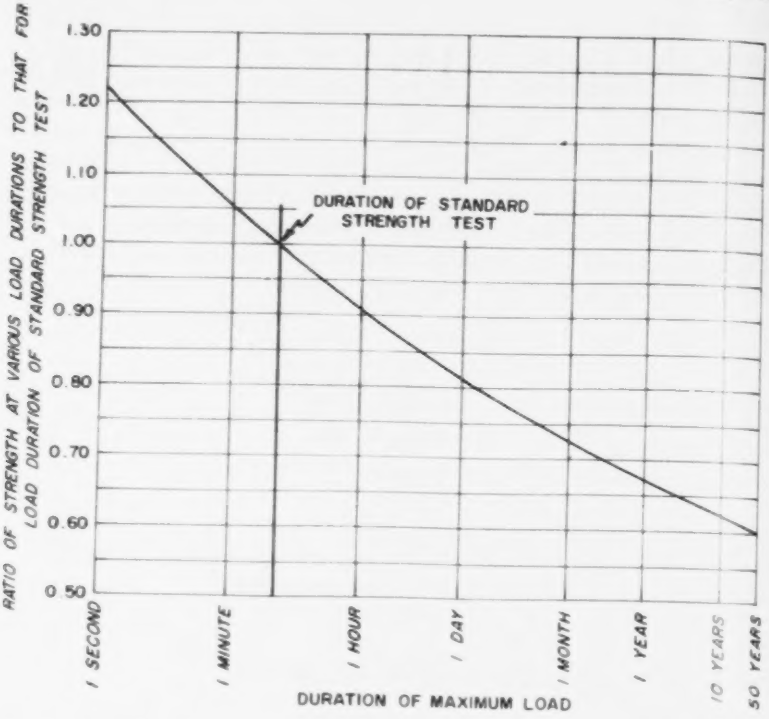

Figure 10-16.—Relation of clear-wood strength of southern pine to duration of load. (Drawing after Liska, J. A. Strength properties of southern pine. Presentation at a symposium, "Utilization of the Southern Pines", Alexandria, La., November 6-8, 1969.)

EXPOSURE TO CHEMICALS

Hardwoods serving in tanks, storage bins, and cooling towers may be exposed to a variety of chemicals in solid or solution form. Certain liquids, such as water and some organic liquids swell wood, and diminish mechanical properties, with no degradation of wood structure; removal of such liquids returns the wood to near original condition. Other liquids such as petroleum and creosote do not swell wood and have virtually no effect on mechanical properties. Liquid ammonia substantially reduces the strength and stiffness of wood, but most of the reduction is regained on removal of the ammonia.

Other chemicals such as alkalis—and to a lesser extent acids—react with wood to change its composition and reduce its strength. Hardwoods are more affected than softwoods. Sapwood, because it is more permeable, is more affected by these chemicals than heartwood. Exposure to certain inorganic salts and contact with some metals also have advserse effects.

Acids.—Wood is resistant to low concentrations of most strong mineral acids and is particularly resistant to organic acids such as acetic. Oxidizing acids (e.g., nitric acid) degrade wood more than non-oxidizing acids.

Lignin is resistant to most acids, especially if cold and dilute. Hemicellulose content, however, is reduced by exposure to acids. For example, Wangaard (1966) found that 4 days of exposure of small white oak specimens to 10-percent hydrochloric acid at 50°C diminished their hemmicellulose content to 36 percent of that before treatment; this same treatment reduced modulus of rupture and work to maximum load to 30 and 12 percent of values before treatment (tables 10-3 and 10-4). Baechler (1954) found that nitric acid reduced the bending strength of maple and white oak across the grain more than sulfuric acid; acetic acid had little effect (table 10-5).

Guy (1946) reported that impregnating wood with coke-oven coal tar with viscosity of 1,250 to 1,450 Saybolt seconds at 200°F will increase the service life of wood exposed to hydrochloric acid 150 to 170 percent. An additional 15-second dip in hot asphalt can further increase service life by 50 to 100 percent. Goldstein (1955) found that impregnation of wood with furfuryl alcohol imparts high resistance to both acids and alkalis.

TABLE 10-3.—*Effect of hydrochloric acid and sodium hydroxide on chemical composition of white oak* (Wangaard 1966)

Duration and temperature of treatment[1] and constituent	10-percent hydrochloric acid	10-percent sodium hydroxide
	Percent (by weight) of original content	
After 32 days at 20°C		
Holocellulose	76.6	84.0
Hemicellulose	58.3	44.7
Alpha cellulose	90.9	114.8
Lignin	107.4	93.1
After 4 days at 50°C		
Holocellulose	64.1	72.6
Hemicellulose	36.0	42.7
Alpha cellulose	90.9	101.1
Lignin	101.0	84.5

[1] Specimens measured 1/2- by 1/2-inch by 9 inches along the grain and, after saturation with water, were soaked in the chemical as specified.

TABLE 10-4.—*Modulus of rupture and work to maximum load of white oak in static bending, as affected by hydrochloric acid and sodium hydroxide* (Wangaard 1966)

Duration and temperature of treatment[1] concentration of chemical (percent)	Modulus of rupture		Work to maximum load	
	HCl	NaOH	HCl	NaOH
	Percent of control			
After 32 days at 20°C				
2	70	26	37	34
10	39	20	12	27
After 4 days at 50°C				
2	51	22	15	26
10	30	15	12	26

[1] Specimens measured 1/2- by 1/2-inch by 9 inches along the grain and, after saturation with water, were soaked in the chemical as specified.

Table 10-5.—*Bending strength of cross sections*[1] *of maple heartwood and white oak sapwood exposed for one to 10 weeks to chemical solutions at two temperatures, expressed as a percentage of strength of sections exposed to water* (Baechler 1954)

Species and chemical	50°C 2-percent solution 1 week	2 weeks	5 weeks	28°C 6-percent solution 1 week	5 weeks	10 weeks
	Percent of control					
Maple heartwood[2]						
HNO_3	38.9	85.5	22.0	—	28.2	—
H_2SO_4	69.5	60.3	50.4	—	61.4	54.0
CH_3COOH	89.3	103.8	83.0	—	87.7	88.2
NaOH	22.7	19.6	17.8	17.6	17.9	—
Na_2CO_3	44.9	43.3	45.1	—	58.2	39.4
White oak sapwood						
HNO_3	44.1	24.1	24.6	—	29.4	—
H_2SO_4	78.9	61.0	40.8	—	70.9	82.5
CH_3COOH	101.5	105.9	91.8	—	103.0	108.5
NaOH	20.6	18.6	17.5	15.0	14.7	—
Na_2CO_3	44.1	39.6	40.6	—	49.5	63.3

[1] Specimens were cross-sectional slices taken from flat-sawn 1 by 4-inch boards; they measured 7/8 by 3-7/8 inches by 3/16 inch along the grain.

[2] *Acer* spp.

Alkalis.—Because of their reaction with both lignin and hemicellulose, alkalis alter wood more drastically than acids of the same concentration. At high temperatures and pressures most of the hemicellulose and a high percentage of the lignin are removed, as in the commercial alkaline pulping of wood. Wangaard (1966) found that four days of exposure of small white oak specimens to 10-percent sodium hydroxide at 50°C reduced hemicellulose and lignin to 42.7 and 84.5 percent, respectively, of their original contents. This treatment also reduced modulus of rupture and work to maximum load to 15 and 26 percent of values in untreated controls (tables 10-3 and 10-4).

Baechler (1954) found that sodium hydroxide solutions weakened white oak specimens slightly more than those of maple (table 10-5); for both species strength loss was substantial.

Salts.—The effect of salts in wood varies with their solubility, the pH of their solutions, and the position they occupy on the lyotropic series (Erickson and Rees 1940).

Information on southern hardwoods is limited. As previously noted in section 10-2 (sub-section IMPREGNATION FOR PRESERVATION), treatment with some preservative or fire-retardant salts significantly reduces modulus of rupture, work to maximum load, and toughness of hardwoods.

Baechler (1954) reported that immersion of small specimens of white oak sapwood and maple in 2- and 6-percent solutions of sodium carbonate caused greater reduction in across-the-grain bending strength than immersion in sulfuric acid of equal concentration and temperature (table 10-5).

Strong solutions of certain inorganic salts can apparently increase some strength properties of wood. Erickson and Rees (1940) reported that all chloride salts tested caused increases in maximum crushing strength parallel to the grain of red pine (*Pinus resinosa* Ait.); for example, wood immersed in a concentrated aqueous solution of calcium chloride had 46 percent greater crushing strength than controls soaked in water. Thiocyanate and iodide salts, however, decreased crushing strength. (For additional data see Koch 1972, p. 617.)

Readers desiring further information on the effects of acids, alkalis and salts on wood, should read Thompson's (1982) review of the subject.

Metals.—Since water in contact with wood always contains electrolytes derived from wood, when two dissimilar metals are inbedded in wood a simple galvanic cell may be formed. If the wood is dampened with salt water, sodium hydroxide forms at the cathode metal and attacks wood adjacent to it. Chlorine is liberated at the anode and due to secondary reactions, may form hydrochloric acid,which attacks both the anode and the adjacent wood. Damage of this type is common where copper and ferrous metals are used together, as in boats or marine structures. Less serious results may ensue, however, under non-marine exposure where two dissimilar metals (e.g., copper and iron) are in contact with damp wood (Evans 1960, Uhlig 1963).

Much more common is the embrittlement and loss of tensile strength of wood in contact with rusting iron; compressive strength may be unaffected. In studying nail holding properties of plain-shank nails driven into green oak (*Quercus* spp.), beech (*Fagus* spp.), and southern pine, Stern (1950) found reductions in withdrawal resistance after the wood had been seasoned for 3 to 7 months; reductions were 5 percent in oak, 52-percent in beech, and 73 percent in southern pine.

The U.S. Department of Agriculture, Forest Service (1974, p. 3-18) explains that iron salts, which develop at points of contact with tie plates, bolts, and the like, have a degradative action on wood, especially in the presence of moisture. In addition, iron salts probably precipitate natural toxic extractives thereby inactivating them and lowering the natural decay resistance of wood. The softening and discoloration of wood around corroded iron fastenings is especially pronounced in acidic woods, such as oak, and in woods which contain considerable tannin and related compounds. The oxide layer formed on iron is transformed through reaction with wood acids into soluble iron salts which not only degrade the surrounding wood but probably catalyze further corrosion of the metal. The action is accelerated by moisture. This effect is not encountered with well-dried wood used in dry locations. Under damp use conditions, it can be avoided or minimized by using corrosion-resistant fastenings. Marian and Wissing (1960abcd) observed that creosote treatment of wood lessened deterioration, but salt-type preservatives promoted it. Service conditions that cause wood to have a pH higher than 4.0 diminish deterioration of wood in contact with iron.

Readers desiring further information should read reviews by Baker (1974) and Graham et al. (1976) on degradation of wood by products of metal corrosion.

10-4 SPECIES-AVERAGE STRENGTH VALUES FOR CLEAR WOOD[5]

Table 10-6 summarizes the important average mechanical properties of stemwood of 23 pine-site hardwoods, in the green condition and at 12-percent moisture content, based on tests at the U.S. Forest Products Laboratory, Madison, Wisconsin, of small, clear, straight-grained specimens. The values are estimates of mean property values for each species. However, some caution is suggested in their use. They were obtained by methods outlined in ASTM D 143-52 (American Society for Testing and Materials 1974d). When the standard was developed there was limited ability to achieve representative sampling. Consequently, the tabulated averages are based on tests of samples from a few subjectively selected trees, mostly from forests as they existed 50 to 60 years ago.

Limitations of the early sampling method preclude making reliable estimates of property variation by species. However, average coefficients of variation of 50 species presented in table 10-7 can be used to estimate the spread of property values associated with table 10-6 values. The properties of approximately 95 percent of the stemwood of a species can be expected to fall in the range of the average value plus or minus twice the product of the coefficient of variation and the average.

A number of tests of mechanical properties of lesser importance than those in table 10-6 are sometimes conducted on small, clear specimens: tension parallel to grain, toughness, torsion, rolling shear, fatigue, and creep. Except for toughness and tension parallel to grain, tests of these minor properties on pine-site hardwoods are too isolated or insignificant to tabulate.

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[5] Text under this heading is condensed (with some additions) from Bendtsen and Ethington (1975).

TABLE 10-6.—*Mechanical properties*[1] *of 24 hardwoods commonly associated with southern pines as determined by the U.S. Forest Products Laboratory from trees of sawlog size* (Bendtsen and Ethington 1975)

Species	Specific gravity[2]	Static bending: Modulus of rupture	Static bending: Modulus of elasticity	Static bending: Work to maximum load	Impact bending—height of drop causing complete failure	Crushing strength parallel to grain	Compression perpendicular to grain stress at proportional limit	Shear strength parallel to grain	Tensile strength perpendicular to grain	Side hardness
		Psi	*10⁶ psi*	*In-lb /in³*	*In*	*Psi*	*Psi*	*Psi*	*Psi*	*Lb*
Ash, green	0.53	9,500	1.40	11.8	35	4,200	730	1,260	590	870
	.56	14,100	1.66	13.4	32	7,080	1,310	1,910	700	1,200
Ash, white	.55	9,600	1.44	16.6	38	3,990	670	1,380	590	960
	.60	15,400	1.74	17.6	43	7,410	1,160	1,950	940	1,320
Elm, American	.46	7,200	1.11	11.8	38	2,910	360	1,000	590	620
	.50	11,800	1.34	13.0	39	5,520	690	1,510	660	830
Elm, winged	.60	9,200	1.21	21.7	73	3,700	630	1,300	850	1,140
	.66	14,800	1.65	23.1	69	6,780	1,020	2,370	1,210	1,540
Hackberry	.49	6,500	.95	14.5	48	2,650	400	1,070	630	700
	.53	11,000	1.19	12.8	43	5,440	890	1,590	580	880
Hickory, mockernut	.64	11,100	1.57	26.1	88	4,480	810	1,280	—	1,440
	.72	19,200	2.22	22.6	77	8,940	1,730	1,740	—	1,970
Hickory, pignut	.66	11,700	1.65	31.7	89	4,810	920	1,370	—	1,520
	.75	20,100	2.26	30.4	74	9,190	1,980	2,150	—	2,140
Hickory, shagbark	.64	11,000	1.57	23.7	74	4,580	840	1,520	—	1,460
	.72	20,200	2.16	25.8	67	9,210	1,760	2,430	—	1,880
Hickory, shellbark	.62	10,500	1.34	29.9	104	3,920	810	1,190	—	1,670
	.69	18,100	1.89	23.6	88	8,000	1,800	[illegible]	—	1,910

See footnotes at the end of table.

TABLE 10-6.—*Mechanical properties*[1] *of 24 hardwoods commonly associated with southern pines as determined by the U.S. Forest Products Laboratory from trees of sawlog size* (Bendtsen and Ethington 1975)—Continued

Species	Specific gravity[2]	Static bending			Impact bending—height of drop causing complete failure	Crushing strength parallel to grain	Compression perpendicular to grain stress at proportional limit	Shear strength parallel to grain	Tensile strength perpendicular to grain	Side hardness
		Modulus of rupture	Modulus of elasticity	Work to maximum load						
		Psi	*10^6 psi*	*In-lb/in^3*	*In*	*Psi*				*Lb*
Maple, red	.49	7,700	1.39	11.4	32	3,280	400	1,150	—	700
	.54	13,400	1.64	12.5	32	6,540	1,000	1,850	—	950
Oak, black	.56	8,200	1.18	12.2	40	3,470	710	1,220	—	1,060
	.61	13,900	1.64	13.7	41	6,520	930	1,910	—	1,210
Oak, cherrybark	.61	10,800	1.79	14.7	54	4,620	760	1,320	800	1,240
	.68	18,100	2.28	18.3	49	8,740	1,250	2,000	840	1,480
Oak, chestnut	.57	8,000	1.37	9.4	35	3,520	530	1,210	690	890
	.66	13,300	1.59	11.0	40	6,830	840	1,490	—	1,130
Oak, laurel	.56	7,900	1.39	11.2	39	3,170	570	1,180	770	1,000
	.63	12,600	1.69	11.8	39	6,980	1,060	1,830	790	1,210
Oak, northern red	0.56	8,300	1.35	13.2	44	3,440	610	1,210	750	1,000
	.63	14,300	1.82	14.5	43	6,760	1,010	1,780	800	1,290
Oak, post	.60	8,100	1.09	11.0	44	3,480	860	1,280	790	1,130
	.67	13,200	1.51	13.2	46	6,600	1,430	1,840	780	1,360
Oak, scarlet	.60	10,400	1.48	15.0	54	4,090	830	1,410	700	1,200
	.67	17,400	1.91	20.5	53	8,330	1,120	1,890	870	1,400
Oak, southern red	.52	6,900	1.14	8.0	29	3,030	550	930	480	860
	.59	10,900	1.49	9.4	26	6,090	870	1,390	510	1,060

See footnotes at the end of table.

TABLE 10-6.—*Mechanical properties*[1] *of 24 hardwoods commonly associated with southern pines as determined by the U.S. Forest Products Laboratory from trees of sawlog size* (Bendtsen and Ethington 1975)—Continued

Species	Specific gravity[2]	Static bending Modulus of rupture	Static bending Modulus of elasticity	Static bending Work to maximum load	Impact bending—height of drop causing complete failure	Crushing strength parallel to grain	Compression perpendicular to grain stress at proportional limit	Shear strength parallel to grain	Tensile strength perpendicular to grain	Side hardness
		Psi	*10⁶ psi*	*In-lb/in³*	*In*	*Psi*				*Lb*
Oak, water	.56	8,900	1.55	11.1	39	3,740	620	1,240	820	1,010
	.63	15,400	2.02	21.5	44	6,770	1,020	2,020	920	1,190
Oak, white	.60	8,300	1.25	11.6	42	3,560	670	1,250	770	1,060
	.68	15,200	1.78	14.8	37	7,440	1,070	2,000	800	1,360
Sweetbay	.45	6,900	1.29	9.2	28	3,120	360	850	—	480
	.47	10,900	1.64	9.2	26	5,680	560	1,680	—	690
Sweetgum	.46	7,100	1.20	10.1	36	3,040	370	990	540	600
	.52	12,500	1.64	11.9	32	6,320	620	1,600	760	850
Tupelo, black	.46	7,000	1.03	8.0	30	3,040	480	1,100	570	640
	.50	9,600	1.20	6.2	22	5,520	930	1,340	500	810
Yellow-poplar	.40	6,000	1.22	7.5	26	2,660	270	790	510	440
	.42	10,100	1.58	8.8	24	5,540	500	1,190	540	540

[1] Values in the first line for each species are from tests of green material; those in the second line are from tests of air-dry material with results adjusted to 12 percent moisture content.

[2] Based on ovendry weight and volume green or at 12 percent moisture content.

TABLE 10-7.—*Average coefficient of variation for specific gravity and mechanical properties in Table 10-6* (Bendtsen and Ethington 1975)[1]

Property	Coefficient of variation
	Percent
Specific gravity	10
Modulus of rupture	16
Modulus of elasticity	22
Work to maximum load	34
Impact bending	25
Crushing strength parallel	18
Compression perpendicular	28
Shear strength	14
Tension perpendicular	25
Side hardness	20

[1] Values given are based on tests of green wood of approximately 50 species. Values for wood adjusted to 12 percent moisture content are comparable.

Strength of three species in tension parallel to the grain is as follows (specific gravity based on ovendry weight and volume when green or at 12 percent moisture content):

Species and moisture content	Specific gravity	Tensile strength
Elm, winged		
12 percent	0.68	27,000
Sweetgum		
Green	.46	13,600
12 percent	.52	17,300
Yellow-poplar		
Green	.42	15,900
12 percent	.46	22,400

Of the nine species for which toughness data are available, true hickories are toughest and sweetbay, sweetgum, and yellow-poplar are least tough (table 10-8).

MODULUS OF ELASTICITY OF STEMWOOD FROM 6-INCH TREES

Modulus of elasticity values, both static and dynamic, for dry stemwood cut from small southern hardwoods of 22 species are shown in table 9-15; their correlation is depicted in figure 9-24. Trees sampled were growing among southern pines.

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TABLE 10-8.—*Average toughness*[1] *values for nine pine-site hardwoods* (Bendtsen and Ethington 1975)

Species and moisture content	Specific gravity[2]	Toughness
		In-lb
Elm, winged		
Green	0.60	670
11 percent	.68	500
Hickory, mockernut		
Green	.64	940
12 percent	.72	790
Hickory, pignut		
Green	.66	1,020
12 percent	.75	860
Hickory, shagbark		
Green	.64	840
12 percent	.72	680
Hickory, shellbark		
Green	.62	1,010
12 percent	.69	1,020
Oak, scarlet		
11 percent	.66	480
Sweetbay		
Green	.44	210
11 percent	.47	170
Sweetgum		
Green	.48	340
13 percent	.51	260
Yellow-poplar		
Green	.43	310
12 percent	.45	220

[1] Average radial and tangential toughness of specimens 2 cm square and 28 cm long.
[2] Based on ovendry weight and volume at moisture content indicated.

ELASTIC CONSTANTS

In certain rigorous stress analyses, elastic constants of wood are required. Limited data on these parameters are available. Radial modulus of elasticity is about double that in the tangential direction; both are only a fraction (about 1/10th and 1/20th) of that parallel to the grain. Ratios of moduli of rigidity (defined in section 10-3, and values for scarlet oak given) to modulus of elasticity in the longitudinal direction range from about 0.01 to 0.09. **Poisson's ratios** vary from about 0.02 to 0.70 (table 10-9), and are affected slightly by moisture content. The six Poisson's ratios are denoted μ_{LR}, μ_{LT}, μ_{RL}, μ_{RT}, μ_{TR}, and μ_{TL}. The first letter of the subscript refers to the direction of applied stress and the second letter refers to direction of lateral deformation. For example, μ_{LR} is the Poisson's ratio for deformation along the radial axis caused by stress along the longitudinal axis.

HARDNESS

Hardwoods, as the name implies, may be used in applications such as residential flooring or truck-bed decking where resistance to indentation, i.e., hardness is required. Of the pine-site hardwoods, the hickories are hardest, requiring 1,810 to 2,140 pounds to imbed a steel ball (0.444 inches in diameter) to half its depth in side grain of dry wood. The oaks, ashes, and winged elm are intermediate in hardness (1,060 to 1,480 pounds), while the remaining seven species listed in table 10-6 are least hard (440 to 950 pounds).

TABLE 10-9.—*Elastic constants of sweetgum and yellow-poplar at 11-percent moisture content* (U.S. Department of Agriculture, Forest Service 1974, p. 4-6)

Property and ratio[1]	Sweetgum[2]	Yellow-poplar[3]
Modulus of elasticity ratios		
E_T/E_L	0.050	0.043
E_R/E_L	.115	.092
Ratio of modulus of rigidity, G, to modulus of elasticity		
G_{LR}/E_L	.089	.075
G_{LT}/E_L	.061	.069
G_{RT}/E_L	.021	.011
Poisson's ratios, μ		
LR	.325	.318
LT	.403	.392
RT	.682	.703
RL	.297	.329
TR	.037	.029
TL	.020	.017

[1] Subscripts L, R, and T correspond to the longitudinal, radial, and tangential directions. For example, G_{LR} is the modulus of rigidity based on shear strain in the LR plane and shear stresses in the LT and RT planes; μ_{LR} is Poisson's ratio for deformation along the radial axis caused by stress along the longitudinal axis.

[2] Specific gravity 0.53 based on ovendry weight and volume at 11-percent moisture content.

[3] Specific gravity 0.38 based on ovendry weight and volume at 11-percent moisture content.

10-5 WITHIN-SPECIES VARIATION IN CLEAR WOOD STRENGTH

A tree of any species can be classified by age class, growth rate, and geographic location. All three factors may be correlated with strength properties of wood cut from the tree; in general, however, the variation in strength properties is attributable to variation in specific gravity. Equations relating mechanical properties to specific gravity are given in tables 10-1 and 10-2, and within-species variations in specific gravity are discussed in section 7-5.

Specific gravity is not the only guide to selection of strong wood, however. For example, Pillow (1939ab) found that white and green ash wood with large average fibril angles had lower strength than wood with moderate or small angles; ash wood from creek-bottom sites had fibrils oriented at larger angles than did wood from upland sites, and had less bending strength and stiffness—even when wood density was comparable (fig. 7-4).

Ash and hickory are valued for their toughness, but variability within species is considerable. Trees with sustained or accelerated ring-width pattern have been found to produce wood of uniformly high toughness from pith to bark. Such vigorously growing trees can be identified by their bark patterns which have relatively low ridges and shallow depressions between them so that the bark appears to be tight. Vigorously growing shagbark hickory trees will shed bark more copiously than slow-growing or stagnated trees (Paul 1947, Pillow 1950).

Paul (1947) suggested limiting the best grades of hickory handles for striking tools to less than 17 rings per inch and at least 55 pounds per cubic foot at 12-percent moisture content. For top-grade ash handles, wood selected should not weight less than 43 pounds per cubic foot at 12-percent moisture content (Pillow 1950).

Readers interested in further information on within species variations of mechanical properties in pine-site hardwoods may find the following references useful:

Species	Reference
Ash, green	Pillow (1939ab)
Ash, white	Baker (1970), Kraemer (1956), Paul (1936), Pillow (1939b)
Elm, winged	Dohr (1953)
Hickory	Boisen and Newlin (1910), Englerth (1951), Paul (1929ab, 1936, 1941, 1947, 1961)
Maple, red	Paul (1941)
Oak, black	Paul (1941, 1963)
Oak, chestnut	Paul (1941)
Oak, northern red	Litwin (1969), Paul (1936, 1941, 1963)
Oak, scarlet	Hamilton (1961), Paul (1941)
Oak, southern red	Paul (1963)
Oak, water	Paul (1963)
Oak, white	Paul (1936, 1941, 1963, 1969)
Sweetgum	Chittenden and Hatt (1905)
Yellow-poplar	Luxford and Wood (1953), Stern (1944b), Paul (1936, 1963), Paul and Norton (1963)

10-6 WITHIN-TREE VARIATION IN CLEAR WOOD STRENGTH

Because specific gravity, fibril angle, tissue percentages, and chemical composition vary across each annual ring, between adjacent rings, with radial position in the stem, and with height above ground, it is reasonable that strength properties should vary with location within trees. Data specific to pine-site hardwoods are scarce, however, and incompletely describe the variation. In the absence of more complete information, the specific gravity variations described in section 7-6—coupled with the equations given in tables 10-1 and 10-2—provide the best available guide to variations in mechanical properties with location in the stem. Limited data on white ash, hickory, southern red oak, sweetgum, and yellow-poplar have been published; these data are summarized in the following sub-sections.

ASH, WHITE

Pillow's (1950) data on upland white ash showed positive correlation between modulus of elasticity and height above ground up to about 10 feet; above that level modulus of elasticity remained nearly constant (fig. 7-3).

Baker (1970) found that toughness of sapwood did not differ from that of heartwood in six white ash trees sampled in central eastern Maine.

HICKORY

Paul (1929ab) concluded that heartwood of hickory is equal to or greater in strength than the white sapwood. Heartwood of the three old-growth pignut hickory trees he sampled in North Carolina and tested green had higher specific gravity than sapwood, with associated higher values for modulus of rupture and modulus of elasticity, as follows:

Property	Heartwood	Sapwood
Rings per inch	18	34
Specific gravity (based on ovendry weight and green volume)	.62	.50
Fiber stress at proportional limit, psi	5,650	4,450
Modulus of rupture, psi	10,800	8,200
Modulus of elasticity, psi	1,720,000	1,090,000
Work to elastic limit, inch pounds per cubic inch	1.07	1.04
Work to maximum load, inch pounds per cubic inch	15.6	17.4
Impact bending strength, height of drop of 50-pound hammer causing complete failure, inches	70	54
Toughness, inch pounds	441	347
Maximum compression strength parallel to grain, psi	4,540	3,600
End hardness, pounds	1,130	850
Side hardness, pounds	1,200	780

Boisen and Newlin (1910) found that in green hickory stemwood, modulus of rupture was maximum at a radius of 3 to 8 inches from the pith, but work to maximum load was greatest near the pith (fig. 10-17). From selected samples of pignut and shagbark hickory and from more numerous samples of shipments of commercial hickories, they concluded that strength and toughness of heartwood is equal to that of sapwood, regardless of color.

Boisen and Newlin's (1910) study also showed that green hickory wood sampled 15 to 35 feet above ground level had greater modulus of rupture than wood taken from butt logs or from topwood; work to maximum load was greatest, however, in wood from near ground level (fig. 10-18).

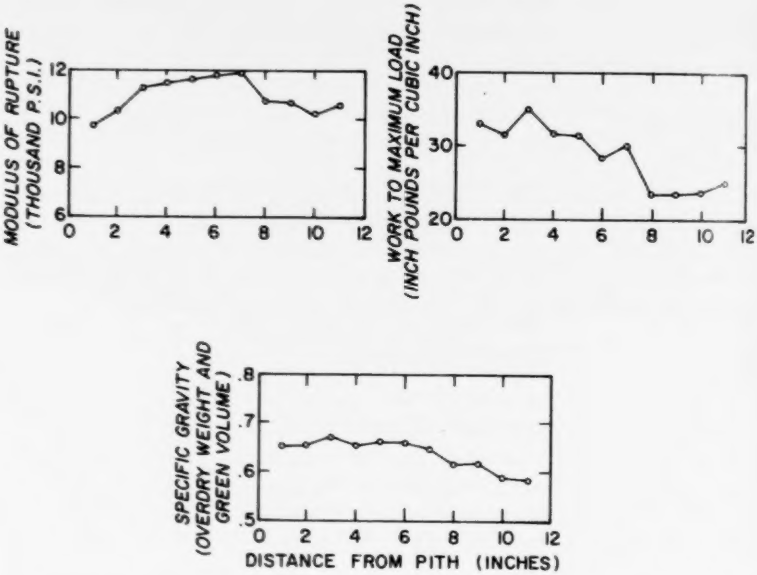

Figure 10-17.—Modulus of rupture, work to maximum load, and specific gravity of green hickory wood related to radial position in the stem. (Drawing after Boisen and Newlin 1910.)

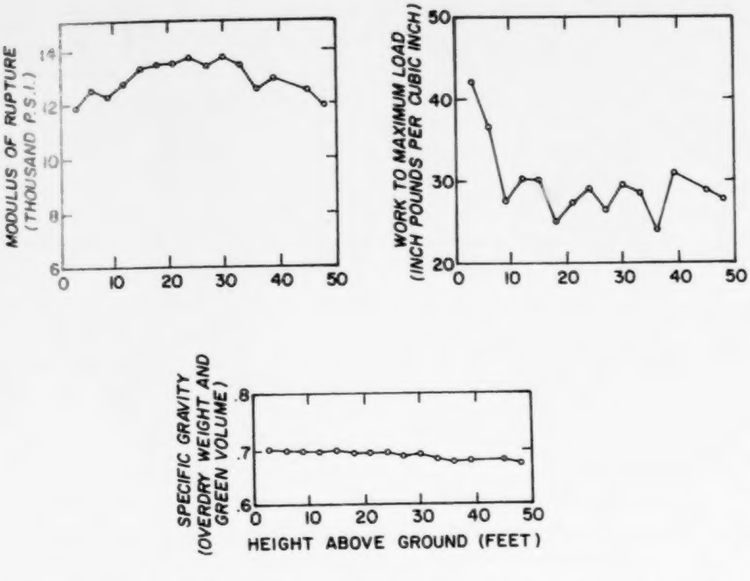

Figure 10-18.—Modulus of rupture, work to maximum load, and specific gravity of green hickory wood related to height in the stem. (Drawing after Boisen and Newlin 1910.)

OAK, SOUTHERN RED

Hamilton (1961), in a study of six dominant or co-dominant, 12-inch and larger southern red oaks from a pine-hardwood stand in Durham County, North Carolina, found that the hardest and toughest wood was located in the lower and upper bole. The middle of the bole was largely composed of wood having the least degree of side hardness and toughness and lacked a central core of high-strength wood (fig. 10-19). (Refer to figure 7-24 for the pattern of specific gravity in these six trees.)

SWEETGUM

Chittenden and Hatt (1905), in tests of wood from a single sweetgum tree grown near Risco, Missouri, found that wood of maximum modulus of rupture, fiber stress at proportional limit, modulus of elasticity and crushing strength parallel to the grain occurred 15 to 25 feet above ground level; wood in the butt log and above 25 feet had slightly lower values for these properties.

In evaluations of green 4- by 4-inch sweetgum specimens from Hollywood, Alabama and Risco, Missouri, these investigators found that sapwood was slightly stronger and stiffer in bending and compression parallel to the grain than discolored heartwood.

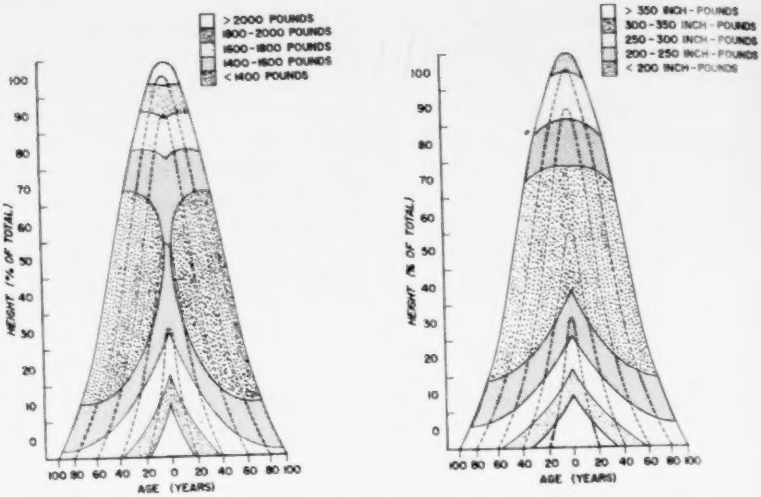

Figure 10-19.—Side hardness (left) and toughness (right) in southern red oak stemwood related to radial position and height. (Drawing after Hamilton 1961.)

YELLOW-POPLAR

Stern's (1944b) study of a single 12-foot-long, 27-inch-diameter yellow-poplar log grown in Virginia's Tazewell County, indicated that most mechanical properties of sapwood did not differ from those of heartwood. In a few properties, (proportional limit and ultimate stress in tension parallel to the grain, and side and end hardness) sapwood was stronger than heartwood; however, sapwood had lower fiber stress at proportional limit in bending than heartwood.

In these tests, heartwood near the pith was significantly weaker than average heartwood in ultimate shear stress parallel to the grain, toughness, and cleavage.

10-7 DESIGN STRESS VALUES[5]

Currently, **design stress** or allowable stress values to be used by architects and engineers, are not assigned to hardwood lumber in the United States (aspen, cottonwood, and red alder excepted) in any nationally recognized document. Yet it is clear from table 10-6 that pine-site hardwoods have the mechanical properties that normally characterize structural materials. Furthermore, hardwoods find numerous structural uses, e.g., as furniture parts, handles of striking tools, sports gear, flooring, stairs and stair railings, highway guardrail posts, and pallets. They are also used on a local basis—sometimes rather extensively—where one might expect stress-graded lumber to be appropriate, e.g., for railroad bridge timbers, sheet piling, shoring, and mine props.

If hardwoods are a suitable structural material, why are they not stress-graded? Galligan (1977) identifies two principal reasons: (1) lack of a unified market demand, and (2) lack of understanding of the stress-grading system and how to develop a market for stress-graded products. He suggests a four-stage approach for achieving stress grading of hardwoods: identify the market, define the grades, assign allowable properties, and provide for acceptance of the system and product.

Southern hardwoods are currently not widely used for structural applications where building codes or regulatory authorities govern. Their structural use in the East, however, in thousands of farm houses and outbuildings not subject to regulatory control, testifies that light frame construction from hardwoods is feasible.

Existing structures were designed on the basis of common sense and tradition. As a more sophisticated alternative, hardwood species capable of matching rule descriptions can be visually graded under the National Grading Rule for Softwood Lumber (given, for example, in "Standard Grading Rules for Southern Pine Lumber," published by the Southern Pine Inspection Bureau, Pensacola, Florida). Allowable properties can be calculated using the principles of ASTM D 245-70 and ASTM D 2555-73 (American Society for Testing and Materials 1974bc). Bendtsen and Galligan (1978) have written a practical guide for the interpretation of these standards. If ASTM D 2555-73 does not list the species of interest, clear-wood mechanial properties must be supplied from some other source, such as table 10-6 of this text. This procedure probably would not be sanctioned by the American Lumber Standards Committee, nor meet with approval of building inspectors or code authorities without considerable scrutiny. Walters et al. 1971 describe some aspects of the problem. Nevertheless, for a person building a structure for himself and who is willing to accept responsibility, it provides some basis for design and a means of reducing his risk.

DESIGN STRESSES FOR PRODUCTS OTHER THAN LUMBER

Bridge stringers or timbers.—ASTM D 2915-74 (American Society for Testing and Materials 1974a) offers still another opportunity for stress-grading hardwoods. This standard may be particularly applicable when the market for a specific product, such as bridge stringers or timbers for powerline towers is sufficiently large. Under this standard, allowable properties would be assigned to grade descriptions written specifically for the products of interest.

Poles and piling.—Design stress values for hardwood poles and piling have not been published. The following publications provide some guidance for producers and users, however:

Subject	Reference
Pile foundation design	American Wood Preservers Institute (1969)
Specifications and dimensions for wood poles	American National Standards Institute (1972)
Derivation of fiber stress from strength values of wood poles (softwoods)	Wood and Marquardt (1965)
Standard specification for round timber piles	American Society for Testing and Materials (1974f)
Standard methods of test of wood poles	American Society for Testing and Materials (1974d)
Standard method for establishing design stresses for round timber piles	American Society for Testing and Materials (1974g)

Plywood.—All plys of stress-graded plywood can be manufactured from sweetgum and yellow-poplar in conformance with U.S. Product Standard PS 1-74 (American Plywood Association 1974), and allowable properties are given in Plywood Design Specification, APA Report Y-510 (American Plywood Association 1978). Inner plys can be of any hardwood species with specific gravity of 0.41 or more, based on ovendry weight and green volume (American Plywood Association 1974b, para. 3.2.3).

Plywood from white ash, American elm, hackberry, red maple, sweetgum, pecan, black tupelo, and yellow-poplar can be manufactured according to Design Guide HP-SG-71 (Hardwood Plywood Manufacturers Association 1971) for interior use only, and allowable properties are given for such plywood.

Lumber laminated from veneer.—Schaffer and Moody (1977) have suggested that hardwood laminated from parallel plys of rotary peeled veneer could provide a stress-rated hardwood lumber product; use of non-destructive stiffness-strength relationships could circumvent the need to develop visual grading procedures. (See Chapter 22 for additional discussion of lumber laminated from veneer.)

Flakeboard.—Design stresses for flakeboard floor decking and roof and wall sheathing made of pine-site hardwoods have not been published. Pearson (1977) has proposed an interim standard, however, for deriving allowable stresses in bending. Jorgensen (1978) has outlined the history of acceptance by building code authorities and regulatory agencies of flakeboard (and their structural particleboards) for use in floors, walls, and roofs. Engineers responsible for development of design stresses for flakeboard are referred to work by McNatt (1975) on effects of rate and duration of loading, and McNatt and Warren (1976) on fatigue properties. Design stresses will vary with species composition and board fabrication procedures. Extensive data on mechanical properties of a few promising designs of hardwood flakeboard are presented in chapter 24.

Fiberboard.—Manufacture of structural fiberboards from a mixture of species may prove to be one of the practical methods of using large tonnages of pine-site hardwoods. McNatt (1970) has described the effect of duration and rate of load on fiberboard strength, and chapter 23 contains data on mechanical properties of fiberboards of various densities and designs. No codified data on design stresses for fiberboards have been published, however.

10-8 NON-DESTRUCTIVE TESTING

Non-destructive grading by mechanical measurement of modulus of elasticity—an alternative or supplement to visual grading—may have special significance in gaining wider acceptance of hardwoods for use in structural applications. Light-frame construction, primarily housing, is the major market for structural lumber and panels. In some of the major structural elements of a house, e.g., joists, beams, roof sheathing panels, and subfloor panels, span length is generally determined by limitations on deflection rather than by strength in bending. Deflection is governed by modulus of elasticity. It is technically possible to measure at production speeds, the modulus of elasticity of every piece of lumber and every panel sold, and to stamp this value on the product. Since this measured value is independent of species, all material of a given modulus of elasticity class could then be used regardless of species for identical spans subject to the same limitations on deflection.

In other structural uses—as in glued laminated beams, trusses, decking, highway posts, handle stock, and sports gear—the strength of wood is more important than its stiffness. For these uses, wood can be mechanically graded for modulus of elasticity and visually graded for strength. Combination of both systems permits greater precision in predicting the actual strength of wood than either system alone.

It is likely that pine-site hardwoods will be increasingly used in structural panels and other composites (see chapters 23 and 24). These more-or-less homogonized products are more readily stress-rated by nondestructive methods than hardwood lumber which is more variable.

One time-tested non-destructive procedure for selecting hickory wood for tool and implement handles, sports equipment and machine parts is the "tone test." The tests consists of dropping a stick of hickory endwise on a concrete floor or other solid base; if a clear ringing sound is produced, the stick is probably reasonably stiff and resilient. If it gives off a dull thudding sound or even a low-pitched tone, however, it is probably too weak or rubbery for use (Heck 1949).

For the reader interested in further study of non-destructive testing, following are three recent and pertinent references: Galligan et al. (1977), Walters and Reiss (1977), and Pellerin and Galligan (1978). Also, Berger (1964) described use of radiography in non-destructive testing of white ash, and Moslemi (1968) analyzed moisture content gradients in white oak and yellow-popular by vibrational techniques. Additional earlier references are listed in Koch (1972, p. 419).

Walters and Reiss (1977) found that the modulus of rupture of small green clear specimens of red oak (*Quercus* spp.) from fifteen sawmills in Illinois could be predicted from their modulus of elasticity in bending with standard error of the estimate of 1,040 psi, as follows ($R^2 = 0.41$):

$$\hat{Y} = 5{,}470 + 3.230X \tag{10-4}$$

where:

$\hat{Y}$ = modulus of rupture, psi
X = modulus of elasticity × 10^{-3}

10-9 LITERATURE CITED

American National Standards Institute. 1972. Specifications and dimensions for wood poles. ANSI 05. 1-1972. 20 p. New York, N. Y.: Am. Natl. Stand. Inst.

American Plywood Association. 1974. Plywood product standard handbook. U. S. Prod. Stand. PS 1-74 for Constr. and Ind. Plywood. 100 p. Tacoma, Wa.: Am. Plywood Assoc.

American Plywood Association. 1978. Plywood design specification. Form. No. Y510E. 30 p. Tacoma, Wa.: Am. Plywood Assoc.

American Society for Testing and Materials. 1967. Standard methods of testing veneer, plywood, and other glued veneer constructions. ASTM Desig. D 805-63. *In* 1967 Annu. Book of ASTM Stand. Part 16. Structural sandwich constructions; wood; adhesives, pp. 225-249. Philadelphia, Pa.: Am. Soc. for Testing and Mater.

American Society for Testing and Materials. 1974a. Standard method for evaluating allowable properties for grades of structural lumber. ASTM Desig. D 2915-74. *In* 1974 Annu. Book of ASTM Stand. Part 22. Wood; adhesives, pp. 805-814. Philadelphia, Pa.: Am. Soc. for Testing and Mater.

American Society for Testing and Materials. 1974b. Standard methods for establishing clear wood strength values. ASTM Desig. D 2555-73. *In* 1974 Annu. Book of ASTM Stand. Part 22. Wood; adhesives, pp. 715-736. Philadelphia, Pa.: Am. Soc. for Testing and Mater.

American Society for Testing and Materials. 1974c. Standard methods for establishing structural grades and related allowable properties for visually graded lumber. ASTM Desig. D 245-70. *In* 1974 Annu. Book of ASTM Stand. Part 22. Wood; adhesives, pp. 114-137. Philadelphia, Pa.: Am. Soc. for Testing and Mater.

American Society for Testing and Materials. 1974d. Standard methods of static tests of wood poles. ASTM Desig. D 1036-58. *In* 1974 Annu. Book of ASTM Stand. Part 22. Wood; adhesives, pp. 257-274. Philadelphia, Pa.: Am. Soc. for Testing and Mater.

American Society for Testing and Materials. 1974e. Standard methods of testing small, clear specimens of timber. ASTM Desig. D 143-52. *In* 1974 Annu. Book of ASTM Stand. Part 22. Wood; adhesives, pp. 34-91. Philadelphia, Pa.: Am. Soc. for Testing and Mater.

American Society for Testing and Materials. 1974f. Standard specification for round timber piles. ASTM Desig. D 25-73. *In* 1967 Annu. Book of ASTM Stand. Part 22. Wood; adhesives, pp. 6-9. Philadelphia, Pa.: Am. Soc. for Testing and Mater.

American Society for Testing and Materials. 1974g. Tentative method for establishing design stresses for round timber piles. ASTM Desig. D 2899-70 T. *In* 1974 Annu. Book of ASTM Stand. Part 22. Wood; adhesives, pp. 802-804. Philadelphia, Pa.: Am. Soc. for Testing and Mater.

American Wood Preservers Institute. 1969. Pile foundations: know-how. 66 p. Washington, D. C.: Am. Wood Preservers Inst.

Atalla, R. H. 1977. Full potential of native cellulose fibers. South. Pulp Pap. Manuf. 40(8):12-15.

Baechler, R. H. 1954. Wood in chemical engineering construction. J. For. Prod. Res. Soc. 4:332-336.

Baker, A. J. 1974. Degradation of wood by products of metal corrosion. U. S. Dep. Agric. For. Serv., Res. Pap. FPL 229. 6 p.

Baker, G. 1970. Some factors affecting the toughness of white ash. For. Prod. J. 20(8):51-52.

Barrett, J. D. 1982. Effects of loading time on design. *In* Structural uses of wood in adverse environments. Symp. Proc., Vancouver, B. C., May 15-18, 1978. (R. W. Meyer and R. M. Kellogg, eds.) p. 301-316. Van Nostrand Reinhold Co., New York.

Barrett, J. D., and R. O. Foschi (Organizing Committee). 1979. Proceedings of the First International Conference on Wood Fracture. August 14-16, 1978, Banff, Alberta, Canada. 305 p. Forintek Canada Corp., Vancouver, B. C.

Bendtsen, B. A. and R. L. Ethington. 1975. Mechanical properties of 23 species of eastern hardwoods. U. S. Dep. Agric. For. Serv., Res. Note FPL-0230. 12 p.

Bendtsen, A., and W. L. Galligan. 1978. Deriving allowable properties of lumber (A practical guide for interpretation of ASTM Standards). U. S. Dep. Agric. For. Serv., Gen. Tech. Rep. FPL 20. 29 p.

Berger, H. 1964. Radiography as a tool of nondestructive testing. For. Prod. J. 14:290-292.

Boisen, A. T. and J. A. Newlin. 1910. The commercial hickories. U. S. Dep. Agric. For. Serv., Bull. 80. 64 p. Washington, D. C.

Campbell, R. N. 1959. Fungus sap-stains of hardwoods. South. Lumberman 199(2489): 115-120.

Chittenden, A. K. and W. K. Hatt. 1905. The red gum. The mechanical properties of red gum wood. U. S. Dep. Agric. Bureau of For., Bull. No. 58. 56 p.

Côté, W. A., and R. B. Hanna. 1983. Ultrastructural characteristics of wood fracture surfaces. Wood and Fiber Sci. 15(2):135-163.

Davis, W. H., and W. S. Thompson. 1964. Influence of thermal treatments of short duration on the toughness and chemical composition of wood. For. Prod. J. 14:350-356.

Dinwoodie, J. M. 1977. Causes of deterioration of UF chipboard under cyclic humidity conditions. Holzforschung 31(2):50-55.

Dohr, A. W. 1953. Southern hard elm strength properties compare favorably with rock elm. South. Lumberman 187(2345):187-188.

Doyle, D. V. 1969. Evaluating appalachian woods for highway posts. U. S. Dep. Agric. For. Serv., Res. Pap. FPL 111. 20 p.

Dreher, W. A., I. S. Goldstein, and G. R. Cramer. 1964. Mechanical properties of acetylated wood. For. Prod. J. 14:66-68.

Englerth, G. H. 1951. Properties and uses of hickory. Cross Tie Bull. 32(11):9-14.

Erickson, H. D. and L. W. Rees. 1940. The effect of several chemicals on the swelling and the crushing strength of wood. J. Agric. Res. 60:593-603.

Evans, U. R. 1960. The corrosion and oxidation of metals. 1094 p. London: Edwards Arnold and Co.

Finnorn, W. J. and R. A. Holcombe. 1959. Bending radii of three thicknesses of tanalith-treated black gum and dense and nondense tanalith-treated hickory. Timber Eng. Co., for Bur. of Ships, Contract No. NObs 77018, 15 p.

Freas, A. D. and F. Werren. 1959. Effect of repeated loading and salt-water immersion on flexural properties of laminated white oak. For. Prod. J. 9:100-103.

Frey-Wyssling, A. 1953. [Fine structure of slip lines in overstressed wood.] Holz als Roh- und Werkstoff 11:283-288.

Galligan, W. L. 1977. Major routes to achieve stress-graded hardwoods. For. Prod. J. 27(2):21-26.

Galligan, W. L., D. V. Snodgrass, and G. W. Crow. 1977. Machine stress rating: practical concerns for lumber producers. U. S. Dep. Agric. For. Serv., Gen. Tech. Rep. FPL 7. 83 p.

Garland, H. 1939. A microscopic study of coniferous wood in relation to its strength properties. Annu. Mo. Bot. Gard. 26:1-95.

Gerhards, C. C. 1977. Effect of duration and rate of loading on strength of wood and wood-based materials. U. S. Dep. Agric. For. Serv., Res. Pap. FPL 283. 24 p.

Gerhards, C. C. 1982. Effect of moisture content and temperature on the mechanical properties of wood. An analysis of immediate effects. Wood and Fiber 14(1):4-36.

Goldstein, I. S. 1955. The impregnation of wood to impart resistance to alkali and acid. For. Prod. J. 5:265-267.

Goodman, J. R. and J. Bodig. 1971. Orthotropic strength of wood in compression. Wood Sci. 4:83-94.

Graham, R. D., M. M. Wilson, and A. Oteng-Amoako. 1976. Wood-metal corrosion. An annotated survey. Res. Bull. No. 21. 34 p. For. Res. Lab., Ore. State Univ.

Guy, H. G. 1946. Use of treated wood under exposure to chemical attack. Am. Wood Preserv. Assoc. Proc. 42:256-262.

Halligan, A. F. and A. P. Schniewind. 1972. Effect of moisture on physical and creep properties of particleboard. For. Prod. J. 22(4):41-48.

Halligan, A. F. and A. P. Schniewind. 1974. Prediction of particleboard mechanical properties at various moisture contents. Wood Sci. and Technol. 8:68-78.

Hamilton, J. R. 1961. Variation of wood properties in southern red oak. For. Prod. J. 11:267-271.

Hardwood Plywood Manufacturers Association. 1971. Structural design guide for hardwood plywood. HPMA Design Guide HP-SG-71. 15 p.

Haygreen, J., H. Hall, K.-N. Yang, and R. Sawicki. 1975. Studies of flexural creep behavior in particleboard under changing humidity conditions. Wood and Fiber 7:74-90.

Heck, G. E. 1949. A tone test for hickory. South. Lumberman 179(2249):268, 270.

Hill, J. L. 1954. The influence of rate of cell formation and certain anatomical characteristics on the strength of Connecticut-grown red oak. D. For. Thesis. 202 p. Yale Univ., New Haven, Conn.

Jorgensen, R. N. 1978. Requirements, codes, and Forest Service goals. *In* Structural flakeboard from forest residues. Proc. of a Symp. presented by the U. S. Dep. Agric. For. Serv., p. 10-12. Gen. Tech. Rep. WO-5. (Kansas City, Mo., June 6-8).

Kellogg, R. M. and F. F. Wangaard. 1964. Influence of fiber strength on sheet properties of hardwood pulps. Tappi 47(6):361-367.

Kennedy, R. W. 1968. Wood in transverse compression—influence of some anatomical variables and density on behavior. For. Prod. J. 18(3):36-40.

Koch, P. 1972. Utilization of the southern pines. U. S. Dep. Agric. For. Serv., Agric. Handb. 420. 1663 p. 2 vol. U. S. Govt. Print. Off., Washington, D. C.

Kraemer, J. H. 1956. Growth-strength relations of white ash—a study of the effects of three influencing factors upon the mechanical properties of the wood of white ash, (*Fraxinus americana*, L.). Agric. Exp. Stn. Stn. Bull. 640, 27 p. Layfayette, Ind.: Purdue Univ.

Kubinsky, E. 1971. Influence of steaming on the properties of *Quercus rubra* L. wood. Holzforschung 25:78-83.

Litwin, P. J. 1969. Effects of rock types and wood characteristics on the hardness of northern red oak wood. M. F. thesis. W. Va. Univ., Morgantown, W. Va. 76 p.

Loos, W. E. and J. A. Kent. 1968. Shear strength of radiation produced wood-plastic combinations. Wood Sci. 1:23-28.

Luxford, R. F. and L. W. Wood. 1953. Survey of strength and related properties of yellow-poplar. U. S. Dep. Agric. For. Serv., FPL Rep. No. 1610. 44 p.

Manwiller, F. G. and P. R. Godfrey. 1973. Microtensile strength of spruce pine after exposure to acids and bases. Wood Sci. 5:295-297.

Marian, J. E. and A. Wissing. 1960a. The chemical and mechanical deterioration of wood in contact with iron. I. Mechanical deterioration. Svensk Papperstidn. 63:47-57.

Marian, J. E. and A. Wissing. 1960b. The chemical and mechanical deterioration of wood in contact with iron. II. Chemical decomposition. Svensk Papperstidn. 63:98-106.

Marian, J. E. and A. Wissing. 1960c. The chemical and mechanical deterioration of wood in contact with iron. III. Effect of some wood preservatives. Svensk Papperstidn. 63:130-132.

Marian, J. E. and A. Wissing. 1960d. The chemical and mechanical deterioration of wood in contact with iron. IV. Prevention of deterioration. Svensk Papperstidn. 63:174-183.

Mark, R. 1965. Tensile stress analysis of the cell walls of coniferous tracheids. *In* Cellular ultra-structure of woody plants, p. 493-533. W. A. Côté, Jr., ed. Syracuse: Syracuse Univ. Press.

Mark, R. E., S. F. Adams, and R. C. Tang. 1970. Moduli of rigidity of Virginia pine and tulip poplar related to moisture content. Wood Sci. 2:203-211.

Markwardt, L. J. and T. R. C. Wilson. 1935. Strength and related properties of woods grown in the United States. U. S. Dep. Agric., Tech. Bull. No. 479. 108 p. Washington, D. C.

McNatt, J. D. 1970. Design stresses for hardboard—effect of rate, duration, and repeated loading. For. Prod. J. 20(1):53-60.

McNatt, J. D. 1974a. Effects of equilibrium moisture content changes on hardboard properties. For. Prod. J. 24(2):29-35.

McNatt, J. D. 1974b. Properties of particleboards at various humidity conditions. U. S. Dep. Agric. For. Serv., Res. Pap. FPL 225. 23 p.

McNatt, J. D. 1975a. Effect of rate of loading and duration of load on properties of particleboard. U. S. Dep. Agric. For. Serv., Res. Pap. FPL 270. 15 p.

McNatt, J. D. 1975b. Humidity effects on properties of structural particleboards from forest residues. U. S. Dep. Agric. For. Serv., Res. Pap. FPL 267. 12 p.

McNatt, J. D. and F. Werren. 1976. Fatigue properties of three particleboards in tension and interlaminar shear. For. Prod. J 26(5):45-47.

Meyer, R. W., and R. M. Kellogg. 1982. Structural uses of wood in adverse environments. Symp. Proc., Vancouver, B. C., May 15-18, 1978. Van Nostrand Reinhold Co., New York. 510 p.

Millett, M. A. and C. C. Gerhards. 1972. Accelerated aging: residual weight and flexural properties of wood heated in air at 115° to 175°C. Wood Sci. 4:193-201.

Moslemi, A. A. 1968. A study of moisture content gradients in wood by vibrational techniques. Wood Sci. 1:77-85.

Page, D. H., and F. El-Hosseiny. 1976. The mechanical properties of single wood pulp fibers. Part 4. The influence of defects. Svensk Papperstidning 79:471-474.

Paul, B. H. 1929a. The quality of Appalachian hickory. South. Lumberman 135(1749):29-32.

Paul, B. H. 1929b. The relation of rate of growth to the production of white wood in hickory trees. South. Lumberman 137 (1765):67.

Paul, B. H. 1936. Second-growth southern hardwood timber. South. Lumberman 153(1937): 115-116.

Paul, B. H. 1941. Quality comparisons of hardwoods from the southern Appalachians with that of northern growth. South. Lumberman 163(2048):35-36.

Paul, B. H. 1947. Guides for the selection of tough hickory. South. Lumberman 175(2193):42, 44.

Paul, B. H. 1961. Preferred woods for tool handles. Hitchcock's Wood Work. Dig. 63(11):56-57.

Paul, B. H. 1963. The application of silviculture in controlling the specific gravity of wood. U. S. Dep. Agric. For. Serv., Tech. Bull. No. 1288. 97 p. Washington, D. C.

Paul, B. H. 1969. Second-growth oak. Part I. The South. Lumber J. 63(1):14-15, 26, 30. Part II. Second-growth oak. The South. Lumber J. 63(1):16-18.

Paul, B. H. and N. A. Norton. 1936. Variations in the wood of yellow-poplar from the southern Appalachian region. J of For. 34:936-942.

Pearson, R. G. 1977. An interim industry standard for deriving allowable unit values for structural particleboard in bending. *In* Proc. of 11th Washington State Univ symp. on particleboard. T. M. Maloney, ed Pullman, Washington: Washington State Univ.

Pellerin, R. F., and W. L. Galligan (co-chairmen). 1978. Proceedings of the fourth nondestructive testing of wood symposium. August 28-30, Vancouver, Wash Eng. Ext. Serv., Washington State Univ., Pullman, Wash. 315 p.

Pillow, M. Y. 1929. Effect of high temperatures on the mode of fracture and other properties of a hardwood. South. Lumberman 137(1766):58, 60.

Pillow, M. Y. 1939a. Characteristics of ash from southern bottomlands. South Lumberman 159(2009):131-136.

Pillow, M. Y. 1939b. White ash and green ash: their wood structure and properties as influenced by growth. Ph. D. thesis. Univ. of Wis., Madison, Wis. 161 p.

Pillow, M. Y. 1950. Guides for selecting tough ash. South. Lumberman 181(2264):42, 46, 48, 50, 52.

Price, E. W. 1974. Analysis of southern hardwoods as furnish for a wood flake-resin composite structural material. Ph. D. thesis. Univ. of Ill., Urbana-Champaign, Ill. 149 p.

Price, E. W. 1976. Determining tensile properties of sweetgum veneer flakes. For. Prod. J. 26(10):50-53.

Princes Risborough Laboratory. 1975 Factors affecting fibre building boards in service. BRE Inf., March 1975, 4 p. Engl.: Princes Risborough Lab.

Przybysz, K., and M. Napiorkowska 1976. (Strength properties of papermaking fibers in fibrous pulps.) Przeglad Papierniczy 32(6):221-224.

Richards, D. B. 1958. Simplified tension tests for wood. For. Prod. J. 8:14-17.

Sauer, D. J. and J. G. Haygreen. 1968 Effects of sorption on the flexural creep behavior of hardboard. For. Prod. J. 18(10): 57-63.

Schaffer, E. L. and R. C. Moody 1977. Stress-graded hardwood lumber by press-lam production? For. Prod. J. 27(2):26-31.

Schniewind, A. P. 1959. Transverse anisotropy of wood: a function of gross anatomic structure. For. Prod. J. 9:350-359.

Shuler, C. E., J. E. Shottafer, and R. J. Campana. 1975. Effect of gamma irradiation *in vivo* on the flexural properties of American elm. Wood Sci. 7:209-212.

Stern, E. G. 1944a. Resistance of common hardwoods to compression perpendicular to the grain. VPI Eng. Exp. Stn. Ser. No. 57, 29 p. Va. Polytech. Inst., Blacksburg, Va.

Stern, E. G. 1944b. Strength properties of yellow-poplar from Virginia. VPI Eng. Exp. Stn. Ser. No. 59, 36 p. Va. Polytech. Inst., Blacksburg, Va.

Stern, E. G. 1950. Deterioration of green wood along steel-nail shank and its influence on the nail-holding properties. Va. J. Sci. 1(3):200-218.

Szabo, T. and G. Ifju. 1970. Influence of stress on creep and moisture distribution in wooden beams under sorption conditions. Wood Sci. 2:159-167.

Tabirih, P. K., E. A. McGinnes, Jr., M. A. Kay, and C. A. Harlow. 1977. A note on anatomical changes of white oak wood upon exposure to gamma radiation. Wood and Fiber 9:211-215.

Tamolang, F. N., F. F. Wangaard, and R. M. Kellogg. 1967. Strength and stiffness of hardwood fibers. J. of the Tech. Assoc. of the Pulp and Pap. Ind. 50(2):68-72.

Tang, R. C., S. F. Adams, and R. E. Mark. 1971. Moduli of rigidity and torsional strength of scarlet oak related to moisture content. Wood Sci. 3:238-244.

Thompson, W. S. 1982. Adverse environments and related design considerations—Chemical effects. *In* Structural uses of wood in adverse environments. Symp. Proc., Vancouver, B. C., May 15-18. (R. W. Meyer and R. M. Kellogg, eds.) p. 117-150. Van Nostrand Reinhold Co., New York.

Thompson, W. S. 1964. Effect of preservative salts on properties of hardwood veneer. For. Prod. J. 14:124-128.

Toole, E. R. 1971. Reduction in crushing strength and weight associated with decay by rot fungi. Wood Sci. 3:172-178.

Ugolev, B. N. 1976. General laws of wood deformation and rheological properties of hardwood. Wood Sci. and Technol. 10:169-181.

Uhlig, H. H. 1963. Corrosion and corrosion control: an introduction to corrosion science and engineering. 371 p. N. Y.: John Wiley and Sons, Inc.

U. S. Department of Agriculture, Forest Service. 1974. Wood handbook: Wood as an engineering material. U. S. Dep. Agric. For. Serv., Agric. Handb. 72, rev. For. Prod. Lab., Madison, Wis.

Walters, C. S. 1967. The effect of treating pressure on the mechanical properties of wood: I. Red gum. *In* Proc. of the sixty-third annu. meet. of the Am. Wood-Preservers' Assoc., vol. 63, pp. 166-186. Washington, D. C.: Am. Wood-Preservers' Assoc.

Walters, C. S., J. K. Guiher, and H. W. Norton. 1971. The statistical reliability of predicting bending strength from strength-ratio tables. For. Prod. J. 21(6):47-57.

Walters, C. W. and W. L. Reiss. 1977. Predicting modulus of rupture from modulus of elasticity for small, clear specimens of oak and cottonwood. For. Prod. J. 27(6):51-53.

Wangaard, F. F. 1966. Resistance of wood to chemical degradation. For. Prod. J. 16(2):53-64.

Wardrop, A. B. 1951. Cell wall organization and the properties of the xylem. I. Cell wall organization and the variation of breaking load in tension of the xylem in conifer stems. Aust. J. Sci. Res. 4B:391-414.

Wengert, E. M. 1979. Relationship between toughness of hardwoods and specific gravity. Wood Sci. 11(4):233.

Wilson, T. R. C. 1932. Strength-moisture relations for wood. U. S. Dep. Agric., Tech. Bull. 282. 88 p. Washington, D. C.

Wolfe, R. W. and R. C. Moody. 1978. Bending strength of water-soaked glued laminated beams. U. S. Dep. Agric. For. Serv., Res. Pap. FPL 307. 12 p.

Wood, L. W., and L. J. Markwardt. 1965. Derivation of fiber stresses from strength values of wood poles. U. S. Dep. Agric. For. Serv. Res. Pap. FPL-39, 8 p.

Young, R. A. and J. A. Meyer. 1968. Heartwood and sapwood impregnations with monomers. For. Prod. J. 18(4):66-68.

Youngs, R. L. 1957. Mechanical properties of red oak related to drying. For. Prod. J. 7:315-324.

11

Attack by Plant Organisms and Insects

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CHAPTER 11

Attack by Plant Organisms and Insects

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CHAPTER 11

Attack by Plant Organisms and Insects

Diseases and insects seldom kill hardwood trees on southern pine sites, but they cause major economic losses by reducing tree growth. More immediately important to manufacturers, decayed or insect riddled trees have less value than sound trees. Also, sawing time for a defective log may exceed that for a sound log by 1 to 1½ minutes (Church 1971). Because increasing numbers of hardwood trees will be harvested complete with branches, bole, and even central stump-root mass, fungus and insect attacks on all tree portions are of interest.

Stored products such as logs, pulpwood, pulp chips, fuelwood, lumber, and veneer can also suffer significant damage from wood infesting insects and stain or decay fungi which are often associated with insect attacks. Most costly to the consumer is insect and decay damage to wood in use, e.g., to structures.

Plant organisms which may degrade wood by feeding on cell-wall substance or cell contents include fungi which cause rots, and others which produce molds and stains. Bacteria also attack and damage wood under some conditions. Storage techniques to protect roundwood and lumber against attack are described in chapter 16, and preservative treatments for hardwood products are discussed in chapter 21. Industrial use of fungal **enzymes** (proteinaceous catalysts) to hydrolyze cellulose is discussed in chapter 26.

Not further discussed in this text are the possibilities of using lignin-degrading fungal enzymes, or micro-organisms that degrade lignin as well as cellulose, in industrial bioconversions. Most experimental organisms used in bioconversion research are apparently without effect on lignin, yet lignin is degraded in nature, just as cellulose is, by microbial enzymes—continuously, efficiently, and on a tremendous scale (Kirk 1975).

11-1 WOOD DESTROYING FUNGI

To live and feed on wood, decay fungi require favorable temperatures (generally between 50° and 95°F), moisture (generally 25 to 100 percent of dry wood weight), and air. Lack of sufficient moisture or air prevents decay; some heartrot fungi in hardwoods are remarkable, however, for their low oxygen demand. Wood kept constantly dry, continuously submerged in water or mud, or buried deep underground is not decayed by basidiomycetous fungi. Dry wood, such as that used in household furniture, contains too little moisture to permit growth of fungi. (A few types of fungi under some conditions can conduct water to dry wood from a distant source and thus make it damp enough to decay; such fungi are sometimes found in buildings, particularly in substructure areas.) Submerged or deeply buried wood, such as piling that supports the masonry foundations of bridges or large buildings, contains too little air to decay. The air supply in soil becomes deficient a few feet below its surface; at depths of 5 to 6 feet, the rate of decay is usually very slow, especially in dense, compact soils. Decay usually extends deepest in light sandy or gravelly soils (U.S. Department of Agriculture, Forest Serivce 1967a).

A likely condition for decay exists when untreated wood is alternately wet and dry, in contact with the ground, or in any situation where it can collect moisture and remain damp for a long time. Decay rate depends on the kind of fungus, character of the wood, and the degree of exposure to moisture, warmth, and air. In warm, humid climates wood used outdoors may decay enough to destroy its usefulness in a few months. In dry or cold climates decay of exposed wood may be so slow as to be scarcely noticed (U.S. Department of Agriculture, Forest Service 1967a).

Of the several thousand wood decay fungi that degrade logging slash, harvested roundwood, and wood products in storage or use, only a small number—a few hundred—are able to decay the hearts of living trees (Wagener and Davidson 1954). *Coriolus versicolor* (L. per Fr.) Quél. (≡*Polyporus versicolor* (L.) per Fr.) destroys hardwood slash and products, and also may cause heartrot in living hardwood trees (Boyce 1961; Davidson et al. 1942). Typically, however, important fungi cause either heartrots or products decay, but not both. Thus *Inonotus rheades* (Pers.) P. Karst. is a major heartrot fungus in hardwoods, while *Phanerochaete chrysosporium* Burds. is important in decaying hardwood logging slash and products (Highley and Kirk 1979). For color illustrations of major decay fungi that attack oaks, see Solomon et al. (1980).

Constraints on heartrotting fungi may include low levels of O_2, high levels of CO_2, concentrations of volatile organic compounds, and interaction with other microbes. Many heartrot fungi cease to decay wood when the host tree dies or is converted into products, probably because of greater fluctuations in temperature and moisture content (Highley and Kirk 1979).

The unbroken bark of living trees affords an effective barrier to fungi. Wind-carried spores usually enter the wood through dead or broken branch stubs, fire scars, or other injuries, or through holes bored by insects; sometimes such insects carry decay spores with them. Control of insects is often a necessary phase of fungus control.

Wood destroying fungi are categorized as causing **white rot, brown rot,** or **soft rot.** These fungi differ significantly in species preferences, rapidity and mode of attack, physiological requirements, and in their effect on physical and mechanical properties of wood.

WHITE ROT

White rot fungi preferentially attack hardwoods (Cowling 1961; Scheffer 1964). *Hericium erinaceum* (Bull. per Fr.) Pers., *Pleurotus sapidus* (Schulze in Kalchhr.) Sace., *Polyporus fissilus* Berk. and Curt. (≡*Tyromycis fissilus* (Berk. and Curt.) Donk), and *Polyporus lucidis* (Curt.) per Fr. (≡*Ganoderma lucidum* (Curt. per Fr.) P. Karst.) are among principal white rot fungi that prosper in fire-scarred or wounded stems of living hardwoods (McCracken 1977), in addition to *Inonotus rheades* previously mentioned. In fire-scarred oaks of the Appalachians, *Xylobatus frustulatum* (Pers. per Fr.) Boidin (≡*Stereum frustulatum* (Pers. per Fr.) Fuckel) called *Stereum frustulosum*, and *Hydnum erinaceus* Bull. per Fr. (≡*Hericium erinaceum*) were the most common decay fungi (Hepting 1941). For white rot fungi associated with decay in living oaks in north central states, see Berry and Lombark (1978). Unprotected hardwood logs and products exposed to conditions conducive to decay are frequently attacked by the white-rot fungi *Schzophyllum commune* Fr., *Coriolus versicolor*, *Stereum complicatum* (Fr.) Fr., *Daedaliopsis confragosa* (Bolt per Fr.) J. Schract. (≡*Daedalea confragosa* (Bolt.) per Fr., and *Stereum frustulatum* (Pers. per Fr.) Boidin, in addition to *Phanerochaete chrysosporium* Burds.

White-rotted hardwood undergoes little surface alteration (fig. 11-1), develops a white or bleached appearance, displays near-normal shrinkage, and in early stages of decay is solid to the touch rather than friable. Both holocellulose and lignin are destroyed, but weight loss is slower than in brown-rotted wood.

Chemistry of attack[1].—White-rot fungi decompose cellulose, hemicelluloses, and lignin at approximately the same relative rates (fig. 11-2). Under the microscope, fungal hyphae are seen to penetrate into, and inhabit, the lumen of every cell in wood that is being attacked. The threadlike hyphae secrete enzymes into the wood surfaces accessible from the lumens; these catalyze a progressive degradation of the components from the lumens outward toward the middle lamella region.

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[1] Text under this heading is condensed from Kirk and Kirk (1978).

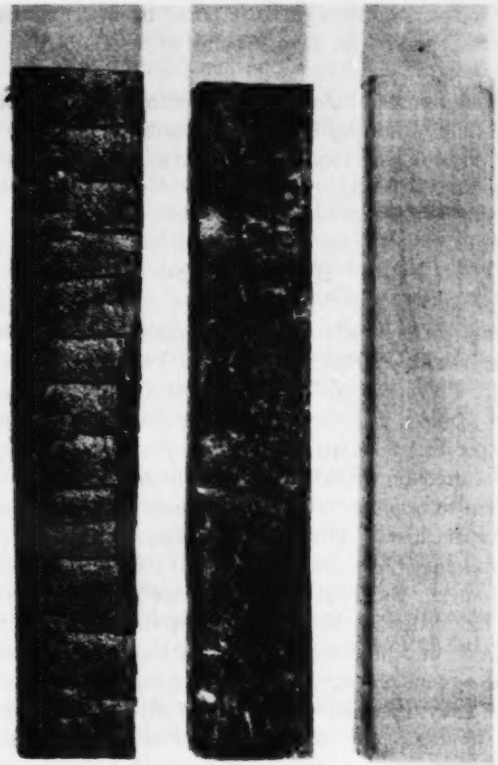

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Figure 11-1.—Checking patterns typical of hardwoods under attack by: (Left) soft-rot fungi; (Center) brown-rot fungi; and (Right) white-rot fungi. (Photo from Cowling 1961.)

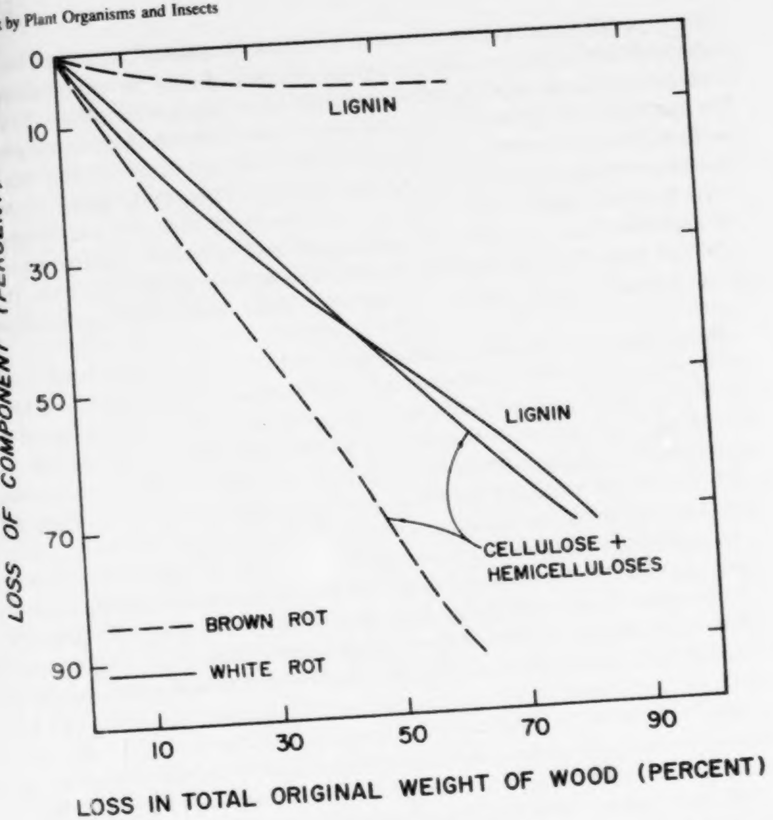

Figure 11-2.—Representative patterns of progressive loss in major structural components of wood by white- and brown-rot fungi. (Drawing after Kirk and Kirk 1978.)

Some enzymes that hydrolyze **cellulose** and **hemicelluloses** attack the chain ends, while others attack within the polymer chains, causing abrupt shortening. Other enzymes break apart the small fragments (sugar oligomers) released by the first enzymes, and still others catalyze hydrolysis of the substituent groups off the hemicellulose backbone chains. The crystalline regions of cellulose fibers are surface-attacked because the enzymes cannot penetrate these tightly packed areas. Exposed cellulose molecules are broken enzymatically by one enzyme, and cellobiose units (two glucoses linked together as they were in cellulose) are removed sequentially from one of the exposed ends by another enzyme. The latter enzyme may also aid in "prying" the chain away from the crystalline region.

Recent findings in Sweden (Eriksson et al. 1974, 1975) have shown that white rot fungi cause several oxidative changes in the sugars formed from the breakdown of cellulose and hemicelluloses. The primary product from cellulose is cellobiose, much of which is oxidized to cellobionic acid, which, in turn, is hydrolyzed to glucose + gluconic acid. Glucose itself is oxidized to gluconic acid, which supports better growth of some fungi than does glucose. Products from hemicelluloses apparently are similarly oxidized.

Evidence also suggests that part of the oxidation of the sugars is coupled to lignin degradation: electrons removed from the sugars serve in certain degradative reactions in lignin involving molecular oxygen. The enzymes that attack **lignin** have not yet been characterized. Whatever their exact nature, these enzymes break lignin down into fragments of component units, and it is these small, probably nonaromatic, fragments that enter fungal cells, where they are metabolized. White rot fungi cannot grow with lignin as sole carbon and energy source; perhaps they expend more energy in degrading it than they obtain by metabolizing the resulting pieces. As in the decomposition of polysaccharides, lignin degradation products do not accumulate during white rot, indicating that the fragments are utilized as they are released (Kirk 1973a).

Mechanics of attack[2].—Activity of white-rot fungal enzymes appears to be confined to close proximity to producing hyphae (Cowling 1961; Wilcox 1968, 1973; Bravery 1971; Greaves 1971; Bravery et al. 1974). In white ash and yellow-poplar under attack by a white-rot fungus (*Coriolus versicolor* (Madison 697)), Peterson (1977) found that hyphal populations first proliferated in rays and vessels; from these centers they advanced, mainly through pits, throughout the wood structure. Among all cellular elements, pits in ray parenchyma cell walls were most often degraded, their canals being enlarged to resemble bore holes. These observations agree with those of Cowling (1961), Wilcox (1965), Bravery et al. (1974), and Jutte and Zabel (1974). Hyphae frequently penetrated ray cell walls, but bore-hole formation between longitudinal elements was scanty, especially in vessels where large lumens and copious pitting permit hyphae to ramify readily. In white ash, tyloses were degraded while underlying vessel walls were intact. Toole (1972) found that in red oak (*Quercus* sp.) also, large vessels provide major avenues for advance of white-rot hyphae. Bore holes, where found in longitudinal cells, were most frequently in the thinner areas of tangential cell-walls; they rarely penetrated the thickened areas at cell corners. White rot hyphae penetrated by complete dissolution of wall polymers in advance of hyphal tips. Hyphae in lumens caused irregular thinning of cell walls, progressing outward from the S_3 layer to the compound middle lamella. Typically, affected walls were furrowed or castellated and in more advanced stages of decay they were often reduced to thin threads. Separations along cell walls were lacking and microvoids in cell walls were generally absent.

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[2] Text under this heading is abstracted from Peterson (1977).

Effect on properties.—Wood under attack by white-rot fungi shows near normal **shrinkage** when dried because cellulose is not substantially depolymerized Scheffer (1936) found that decay of sweetgum by the white rot *Coriolus versicolor* lowered most strength values more rapidly than specific gravity. Cartwright and Findlay (1958) concluded that white rots rapidly reduce **toughness**, but that they probably reduce other strength properties less rapidly than brown rots. Richards (1954) observed the following correlation between toughness of sweetgum sapwood and weight loss from decay by the white-rot fungus *C. versicolor:*

Weight loss	Toughness	Specific gravity (ovendry weight and green volume basis)
Percent	*Inch-pounds*	
0.0	104	0.43
4.4	29	.41
5.8	26	.40
8.3	16	.40
10.6	15	.38
14.0	14	.37
17.8	13	.35
21.4	13	.34

During weight loss of 21.4 percent, wet volume remained unchanged, but moisture content rose from about 30 percent to 60 percent of dry weight. At 10-percent weight loss, specimens retained only about 15 percent of their original toughness.

While white-rot fungi reduce toughness more drastically than brown-rot at equal weight loss, they are only half as effective in reducing **tensile strength** in beech (*Fagus* sp.) in the incipient state of decay (Great Britain Department of Science and Industry 1950). Cartwright et al. (1936) found that **modulus of rupture** decreased only 1.8 percent in ash (*Fraxinus excelsior* L.) decayed by the white rot *Polyporus hispidis (Ednonatus hispidus* (Bull. per Fr.) P. Karst. to the extent of 1.4 percent weight loss. In a study of 11 woods (10 of them hardwoods including white oak), Kennedy (1958) found that a weight loss of 5 percent from decay by the white-rot fungus *C. versicolor*, caused an average loss in modulus of rupture of about 25 percent; loss of **work to maximum load** averaged about 43 percent at this weight loss. White-rotted woods lost less of these strength properties than brown-rotted woods at the same percent of weight loss.

At any weight loss from attack by the white-rot fungi *C. versicolor* and *Hirschioporus abietinus* (Pers. per Fr.) Donk (≡*Polyporus abietinus* (Pers.) per Fr.), sweetgum lost less **crushing strength** perpendicular to the grain than did southern pine (fig. 11-3 illustrates the effect of *C. versicolor*). Of the major mechanical properties, **modulus of elasticity** appears to be least affected by fungal attack (Cartwright and Findlay 1958).

White-rotted wood gives near normal yields of pulp having normal strength properties, because cellulose is not substantially depolymerized. **Solubility** of white-rotted wood in a variety of solvents also remains relatively unaffected even after substantial weight losses (fig. 11-4).

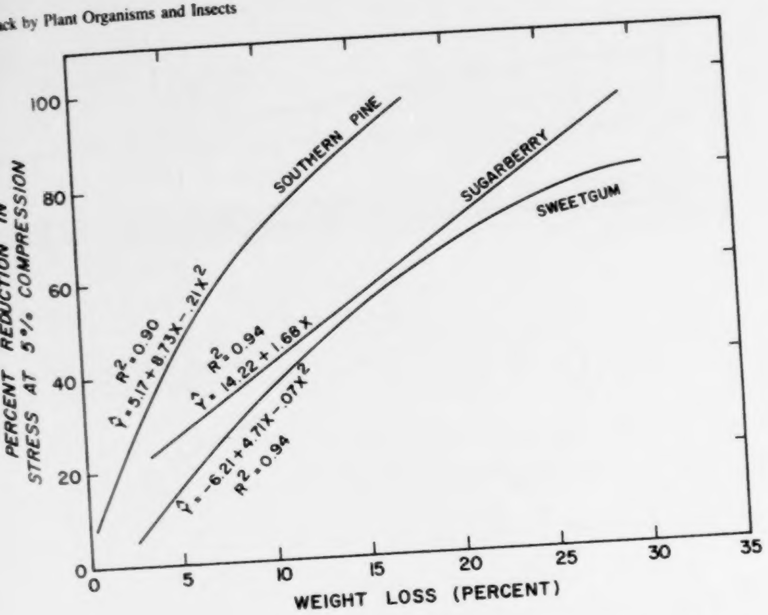

Figure 11-3.—Reduction of stress at 5-percent strain in compression perpendicular to the grain in southern pine, sugarberry, and sweetgum related to weight loss from attack by the white-rot fungus *Coriolus versicolor*. (Drawing after Toole 1971.)

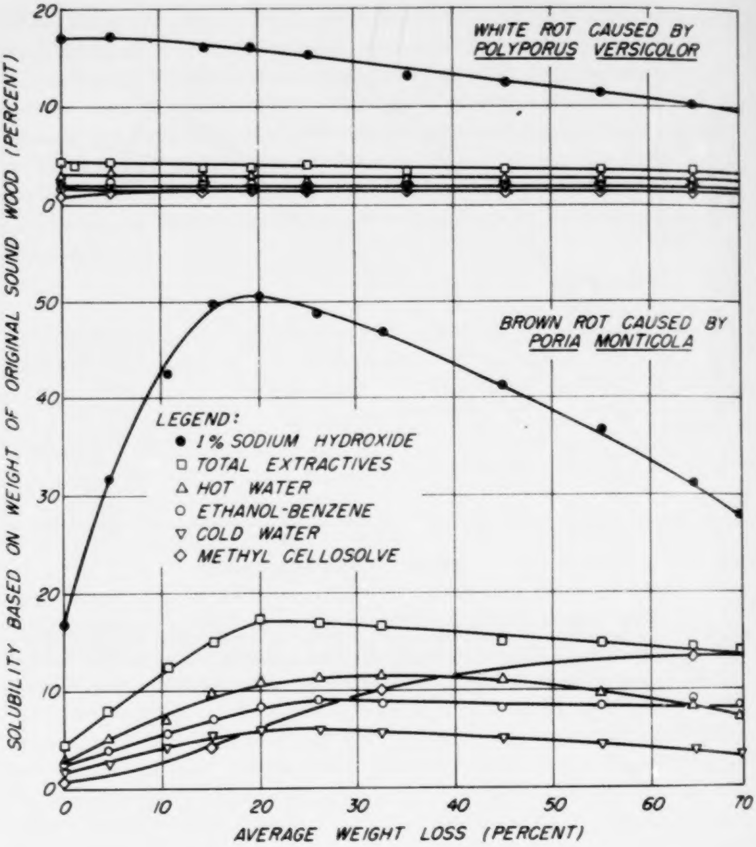

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Figure 11-4.—Solubility of sweetgum sapwood in progressive stages of decay by white- and brown-rot fungi. Current terminology calls for *Coriolus versicolor* (instead of *Polyporous versicolor*) and *Poria placenta* (instead of *Poria monticola*).

BROWN ROT

Although brown-rot fungi preferentially attack softwoods, they commonly attack hardwood logging slash and harvested hardwoods; important among such fungi are the following species:

Daedalea quercina L. ex. Fries
Polyporus palustris Berk. and Curt. (≡*Tyromyces palustris* (Berk. and Curt.) Murr.)
Poria incrassata (Berk and Curt.) Burt.
Poria oleracea Davidson and Lombard
Poria placenta (Fr.) Cooke (often referred to as *Poria monticola* Murr.)
Lenzites trabea (Pers. per Fr.) Fr. (≡*Gloeophyllum trabeum* (Pers. per Fr.) Murr.)

A few brown-rot fungi cause significant heartrot in living trees, e.g.:

Polyporus sulphureus (Bull.) per Fr. (≡*Laetiporous sulphureus* (Bull. per Fr.) Murr.)
Polyporus spraguei Berk. and Curt. in Berk. (≡*Tyromyces spraguei* (Berk. and Curt.) Murr.)
Poria cocos (Schw.) Wolf
Poria oleracea Davidson and Lombard

For brown-rot fungi associated with decay in living oak trees of north central states, see Berry and Lombark (1978).

Brown-rotted hardwood develops a reddish-brown color, looks charred (fig. 11-1), is friable, and on drying shrinks excessively—especially longitudinally (Scheffer 1936; Buro 1954; Toole 1970). Weight loss in brown-rotted wood results primarily from destruction of cellulose in the S_2 layer of cell walls (Cowling 1961). Under laboratory conditions, such weight loss can exceed 50 percent of wood dry weight after only 3 months of exposure (Smith and Gjovik 1972).

Brown-rot fungi can be detected in incipient or advanced stages by staining affected wood with osmium tetroxide (Cowling and Sachs 1960). Wood destroying fungi, including the brown-rotter *Gloephyllum trabeum* can be killed by heating according to the following schedule (Chidester 1939):

Temperature	Time
°F	*Min.*
150	75
170	30
180	20
200	10
212	5

Chemistry of attack[1].—Brown rot fungi, like white rot fungi, inhabit the cell lumens. Soon after becoming established, these fungi very rapidly break (depolymerize) the long cellulose chains into short fragments, transforming the tough, strong wood fibers into brittle, weak ones. As decay proceeds, the cellulose fragments and the hemicelluloses are destroyed at approximately the same relative rates (fig. 11-2). The lignin content is only slightly decreased and the lignin polymer is only slightly modified, leaving it largely intact as a brown, crumbly residue.

The paradox of how brown-rot fungi can decay wood has puzzled scientists for many years. Ordinarily, cellulose is not chemically accessible to enzymes unless the associated lignin is degraded, but these fungi depolymerize and consume cellulose while leaving the lignin chemically intact. Evidence now suggests that these fungi attack cellulose initially with extracellular hydrogen peroxide, which reacts with trace quantities of iron in the wood to cause oxidative polymerization of cellulose (Koenigs 1974). This apparently provides access to the polysaccharides by enzymes similar to those of white-rot and soft-rot fungi. Such access enables these fungi to degrade cellulose without first breaking down the lignin, but otherwise their enzymes function in the same manner as those of white and soft rots (Kirk and Kirk 1978).

Mechanics of attack.—Peterson (1977) studied ultrastructure of brown-rotted green ash and yellow-poplar. While cell walls were decomposed by hyphae in both bore holes and lumina, general dissolution of secondary wall constituents proceeded overwhelmingly from lumen-situated hyphae. Bore holes were erratically or sparsely distributed in longitudinal elements, except those adjacent to rays, so that large areas of cell walls were extensively degraded without hyphal penetration via bore holes. Hyphae most frequently utilize pit apertures to gain cell entry (Jutte and Zabel 1974). Wilcox (1968), in a light-microscope study of sweetgum, found that brown-rot fungus removed the S_2 layer before the S_1 and S_3 layers; the cellulolytic enzymes of the brown-rot fungus apparently penetrated and acted on layers within secondary walls. In this study of brown-rotted sweetgum, average cross-sectional area of cells did not change. Degradation of hardwood tissue types is variable and apparently species dependent. In *Fagus* sp. (Wilcox 1973) and an unidentified red oak (Toole 1972) vessels were particularly degraded in advanced brown rot; in brown-rotted birch (*Betula* sp.) all cells except latewood fibers were extensively decomposed (Greaves and Levy 1965).

Effect on properties.—Weight loss in hardwood from brown-rot fungi is usually, but not always, accompanied by abnormal shrinkage (Richards 1954). Toole (1970) found that three species of pine-site red oaks (cherrybark, southern red, and water oaks) inoculated with *Gloephyllum trabeum* (Madison isolate 617) and incubated until weight loss averaged 48 percent, shrank in the tangential direction from 0 to 24 percent (avg. 5 percent) more than undecayed blocks when dried to constant weight at 26.7°C and 70 percent relative humidity.

Loss of hardwood weight from attack by brown-rot fungi is well correlated with loss in modulus of elasticity, proportional limit, and stress at 5 percent strain in compression perpendicular to the grain (Toole 1971); hardwoods appear to lose less strength than southern pine, however (fig. 11-5).

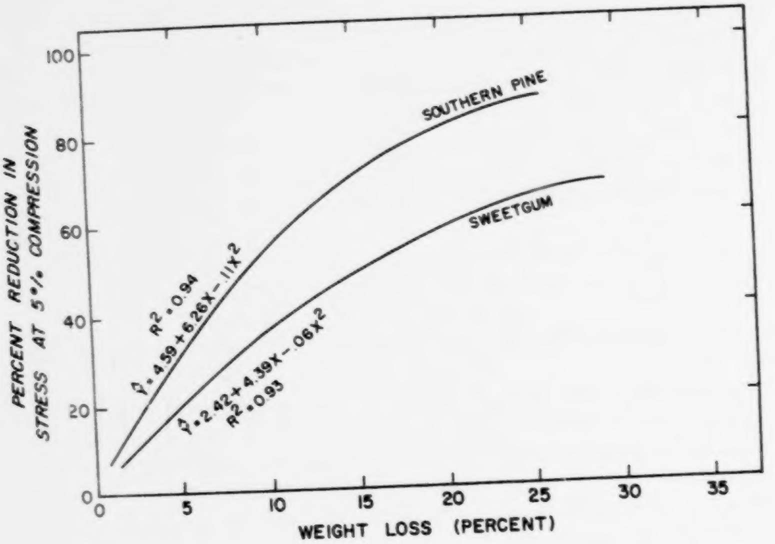

Figure 11-5.—Reduction of stress at 5-percent strain in compression perpendicular to the grain in sweetgum and southern pine related to weight loss from attack by three brown-rot fungi. (Drawing after Toole 1971.)

In a study of 11 woods (ten of them hardwoods including white oak), Kennedy (1958) found that attack by the brown-rot fungus *Poria placenta* (as *P. monticola*) reduced modulus of rupture and work to maximum load in static bending more than equivalent weight loss from action of the white-rot fungus *Coriolus versicolor*. Kennedy concluded that species differed greatly in strength retention when decayed to equal weight losses by the brown-rot fungus; in some specimens modulus of rupture and work to maximum load were drastically reduced with little or no weight loss. Strength loss was proportional to solubility of the decayed wood in 1 percent NaOH, however, indicating correlation with depolymerization of the cellulose.

Richards (1954) observed the following correlation between toughness of sweetgum sapwood and weight loss from decay by the brown-rot fungus *G. trabeum*:

Weight loss	Toughness	Specific gravity (ovendry weight and green volume basis)
Percent	*Inch-pounds*	
0	103	0.43
1.7	66	.42
4.0	78	.41
9.4	45	.40
12.9	24	.38
13.5	19	.37
16.6	24	.37
20.0	16	.35

At a weight loss of only 10 percent, toughness was diminished by more than half.

Brown-rotted wood gives low yields of poor-quality pulp (Martin 1956; Sheridan 1958) because holocellulose in such wood has been severely depolymerized (Cowling 1961). Up to 20-percent weight loss, brown-rotted sweetgum shows sharply increasing solubility in 1 percent NaOH; solubility in methyl cellosolve—which has an affinity for lignin—is positively correlated with percent weight loss (fig. 11-4).

SOFT ROT

White-rot and brown-rot fungi are, for the most part, Basidiomycetes. Soft rotters, however, are Ascomycetes or Fungi Imperfecti; they appear to be more prevalent in hardwoods than in softwoods (Duncan 1960). These soft-rotting fungi, whose attack resembles—but is slower than—that of white-rot fungi, are unusual in that some of them can degrade the surface of wood that is hot (up to about 100°F), thoroughly soaked in water, and low in air supply, e.g., in wooden slats of industrial cooling towers over which water flows continuously (Findlay and Savory 1950, 1954; Savory 1954a, 1954b, 1955; Savory and Pinion 1958; Duncan 1961). Additionally, many soft-rot fungi can tolerate quite high levels of commonly used wood preservatives, with consequent premature failure in service (Dale 1976).

The U.S. Forest Products Laboratory in Madison, Wis., has isolated more than 150 fungi from soft-rotted wood, the majority of which have produced rot under laboratory conditions. Savory, in England, observed that several species of *Chaetomium* Kunge can cause considerable rot in beech, and *C. globosum* Kunge per Fr. has probably been the soft-rot fungus most studied. Other soft-rotting fungi more prevalent in the United States have been listed by Duncan (1960, 1965). See also, Stewart et al. (1979) for an indexed bibliography of Ascomycetes that occur in wood.

The surface of wood kept wet or submerged in water for a number of years becomes darkened and softened if attacked by soft-rot fungi. While still wet, the softened surface can easily be scraped away to reveal relatively sound wood. When dried, the wood usually retains its shape and may appear normal, though it breaks with a brash fracture. In wood subjected to very wet conditions and leaching, small surface cracks develop across the grain, giving the darkened surfaces an appearance resembling lightly charred wood (fig. 11-1).

Chemistry of attack.—Soft-rot fungi attack hardwoods more rapidly and extensively than they do softwoods. Although their attack is much slower, soft rot fungi cause the same general pattern of degradation as white rot fungi, except that lignin is depleted much more slowly than are cellulose and hemicelluloses. The hemicellulose- and cellulose-degrading enzymes of soft rots have not been studied in as much detail as those of the white rots, but available data suggest a basic similarity to the white rot system (Eslyn et al. 1975; Kirk and Kirk 1978).

Mechanics of attack.—The physical mode of attack on wood by soft-rot fungi differs entirely from that of white- or brown-rot fungi. Soft-rot hyphae penetrate longitudinally into the S_2 layer of cell walls, creating conical cavities as they destroy the wood substance. These cavities are, however, more pronounced in softwoods than in hardwoods, where the attack preferably occurs from the cell lumen. Thus in hardwoods the S_3 layer is often subjected to direct enzymatic attack by hyphae growing on the cell wall. Vessels are generally less deteriorated than fibers (Liese 1970). Zainal (1978) compared the several theories of cavity formation as observed in both hardwoods and softwoods, and concluded that the pointed ends found in these cavities are brought about by inhibition of enzyme activity, perhaps from deposition of inhibiting material, at the ends of proboscis hyphae.

NATURAL DECAY RESISTANCE

The natural decay resistance of pine-site hardwoods is in the heartwood (see subsection SAPWOOD AND HEARTWOOD in sect. 5-1 for a discussion of heartwood formation and proportion of tree volume). When untreated, the sapwood of all the species has low decay resistance and generally short life under decay-producing conditions. For example, sapwood of white oak—one of the most durable pine-site hardwoods—loses weight about twice as fast as heartwood when exposed in outdoor ground contact to the wood destroying fungi *Poria incrassata* (Berk. and Curt.) Burt and *Merulius lacrymans* (Wulf.) per Fr. (≡*Serpula lacrymans* (Wulf. per Fr.) Schroth) (Diller and Koch 1959).

The decay resistance of sapwood varies significantly with fungi. Among sapwoods of 14 domestic softwood species plus one unidentified species of eucalyptus in non-ground-contact decay tests, the eucalyptus sapwood was among the species most resistant to brown-rot, but was one of the least resistant to white-rot; it was intermediate in resistance to soft-rot (Eslyn and Highley 1976).

In heartwood also species-fungus interactions affect rate of weight loss from decay. Scheffer et al. (1949) found that chestnut oak outer heartwood suffered faster weight loss from the white-pocket rot fungus *Xylobalus frustulatum* (as *S. frustulosum*) than from the brown rotters *Poria placenta* (Fr.) Cooke (as *P. monticola* Murr.) and *Gloeophyllum trabeum*; in three other white oaks and in three red oaks, however, *P. placenta* caused greatest weight loss (fig. 11-6). Of the seven oak species studied, outer heartwood from chestnut oak was most resistant to decay, and that from scarlet oak was least resistant; the four white oaks were more resistant to decay than the three red oaks (fig. 11-6).

Carter et al. (1976) evaluated decay resistance of wood sampled from nine or ten trees of each of 22 pine-site hardwoods. The trees measured 6 inches at breast height (average age was 39 years) and specimens were taken 6 feet above ground level and in outer heartwood when possible. In green and white ash where the heartwood zone is small, blocks were cut to include as much heartwood as possible; in species without visible heartwood, specimens were taken from the inner third of the distance from pith to bark. Specimens were exposed to the brown rot fungus *Gloeophyllum trabeum* in soil-block decay chambers according to procedures outlined by American Society for Testing and Materials (1972).

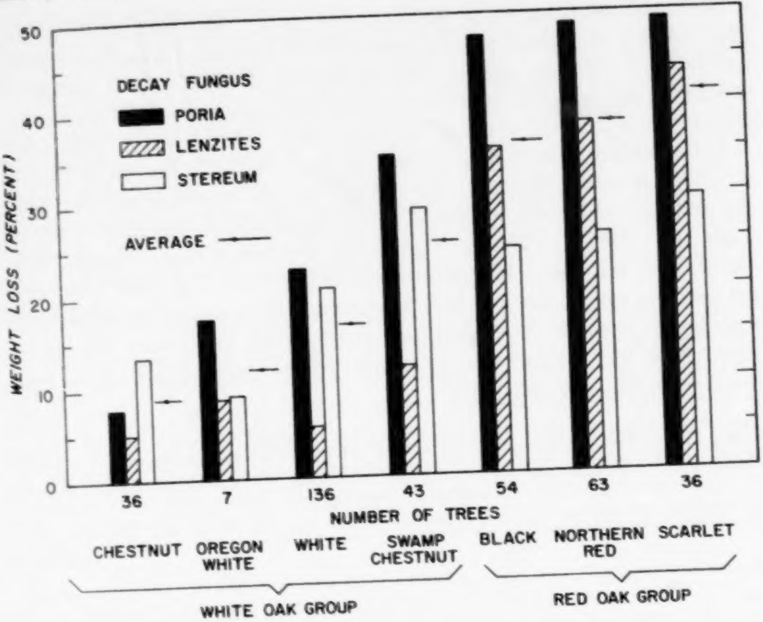

Figure 11-6.—Average weight loss caused by decay from two brown rots and one white-pocket rot in outer heartwood taken at breast height from four white oaks and three red oaks. Specimens were exposed 4 months in culture bottles held at 80°F. Oregon white oak is *Q. garryana* Dougl., and swamp chestnut oak is *Q. michauxii* Nutt. Current terminology calls for *Poria placenta* (instead of *Poria*), *Gloeophyllum trabeum* (instead of *Lenzites*), and *Xylobalus frustulatum* (instead of *Stereum*). (Drawing after Scheffer et al. 1949.)

In several cases, the small-diameter, slow-grown, and often poorly formed trees sampled on southern pine sites proved more resistant to decay than sawlog-size trees of the same species. The heartwood of white oaks is considered resistant to very resistant; that of red oaks, hickory, and green ash is described as slightly resistant to non-resistant (Scheffer 1943; Scheffer and Cowling 1966; U.S. Department of Agriculture, Forest Service 1967b). In the test of Carter et al. (1976), however, blackjack oak—a member of the red oak group—and white and post oaks had lowest weight losses caused by decay—less than 10 percent (table 11-1). Hickory, white ash, green ash, and four red oaks—laurel, black, southern red, and water—had weight losses of only 20 to 31 percent. Three other red oaks and winged elm lost 36 to 40 percent of their weight but did not differ significantly from the 20 to 31 percent group except for hickory. The species shown to be least resistant were sweetgum, yellow-poplar, black tupelo, hackberry, sweetbay, and red maple.

TABLE 11-1.—*Percent of original dry weight lost by 22 pine-site hardwoods*[1] *in standard exposure (American Society for Testing and Materials 1972) to Gloeophyllum trabeum* (Carter et al. 1976)

Species	Decay[2]
	Percent
Blackjack oak[3]	8
White oak	8
Post oak[3]	9
Hickory, true	20
Laurel oak	26
Black oak	27
Southern red oak	28
White ash[3]	29
Water oak	30
Green ash	31
Shumard oak	36
Northern red oak	38
Scarlet oak	39
Winged elm	40
Cherrybark oak	41
American elm	43
Sweetgum	59
Yellow-poplar	62
Black tupelo	64
Hackberry	64
Sweetbay[3]	66
Red maple	67

[1] Ranked from most resistant to most susceptible; means connected by a line are not significantly different at the 0.05 level of probability (Duncan's multiple range test).

[2] Decay data were transformed to arc sine for analysis but are presented as retransformed data in the table.

[3] Nine rather than 10 trees tested.

Variations within species.—Data on within-species variation are scanty. Scheffer et al. (1949) found substantial differences in heartwood decay resistance between individual oak trees of the same size and species in a locality. Toole and Darwin (1970) studied within-species variation of heartwood resistance to white- and brown-rot fungi of water, cherrybark, and southern red oaks. They observed great variation in decay resistance among trees within species. Scheffer and Cowling (1966) concluded from a review of the literature that individual trees within a species vary considerably in decay resistance. All three groups concluded that much of the variation is genetically controlled; the 1966 study also attributed some variability to tree size and age, but very little to site differences.

A marked tendency for decay resistance of outer heartwood of white oak to increase with size of tree was observed by Scheffer et al. (1949); in this study, breast-height samples were taken from 32 trees in a single even-aged closed stand (fig. 11-7). Tryon et al. (1975), however, found no significant relationship between width of annual rings and decay resistance of outer heartwood of white oak and northern red oak; the breast-height samples in their study, which were from eight even-aged stands on high- and low-quality sites, were subjected to attack by the brown-rot fungus, *G. Trabeum* and the white-rot fungus *C. versicolor*.

Variations within trees.—The most striking variation of decay resistance within trees is that between sapwood and heartwood (fig. 11-8). In the heartwood, decay resistance may decrease with increased distance from the sapwood (fig. 11-9). The relationship appears to be dependent on the decay fungus, however, since all basal heartwood of the four oaks illustrated in figure 11-9 was equally resistant to the white-rot fungus *C. versicolor*, regardless of radial position (Scheffer et al. 1949). Where radial differences are prominent, there may be differences vertically in the tree; the patterns of variation are complex. Scheffer and Cowling (1966) concluded from a survey of the literature that in many wood species the following generalizations are applicable:

- Decay resistance decreases progressively from the outer heartwood to the pith.
- Decay resistance of outer heartwood decreases progressively from the base of the tree upward, whereas the opposite is true of inner heartwood.
- Outer heartwood at the base of a tree is most resistant and inner heartwood at the base is least resistant; heartwood in the upper bole is intermediate between these extremes.
- The larger the tree, the more resistant is the outer heartwood at the base and the less resistant is the inner heartwood.

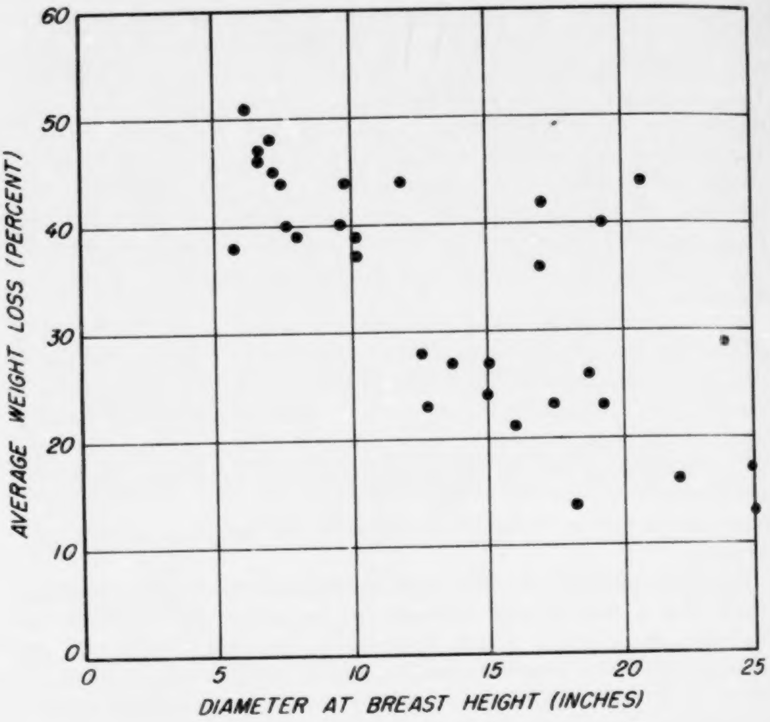

Figure 11-7.—Relation between the diameter of white oak (*Quercus alba*) trees in a single stand and the weight loss caused by decay in samples from their outer heartwood. Each point represents the average weight loss caused by *Poria placenta* (as *P. monticola*), *Coriolus versicolor*, and *Xylobalus frustulatum* in six cores from each tree. The correlation coefficients relating dbh to weight loss caused by these fungi individually were -0.72, -0.75, and -0.73, respectively. (Drawing after Scheffer et al. 1949.)

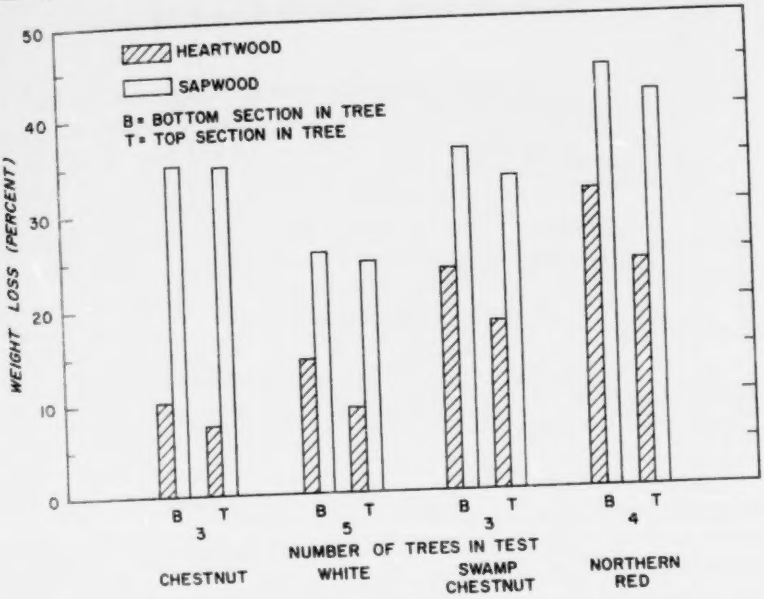

Figure 11-8.—Weight losses caused by decay in oak blocks from the outer heartwood and in adjacent sapwood blocks. Losses are averages of the indicated number of trees and for decay caused by *Poria placenta* (as *P. monticola*), *Gloeophyllum trabeum*, and *Xylobalus frustulatum*. (Drawing after Scheffer et al. 1949.)

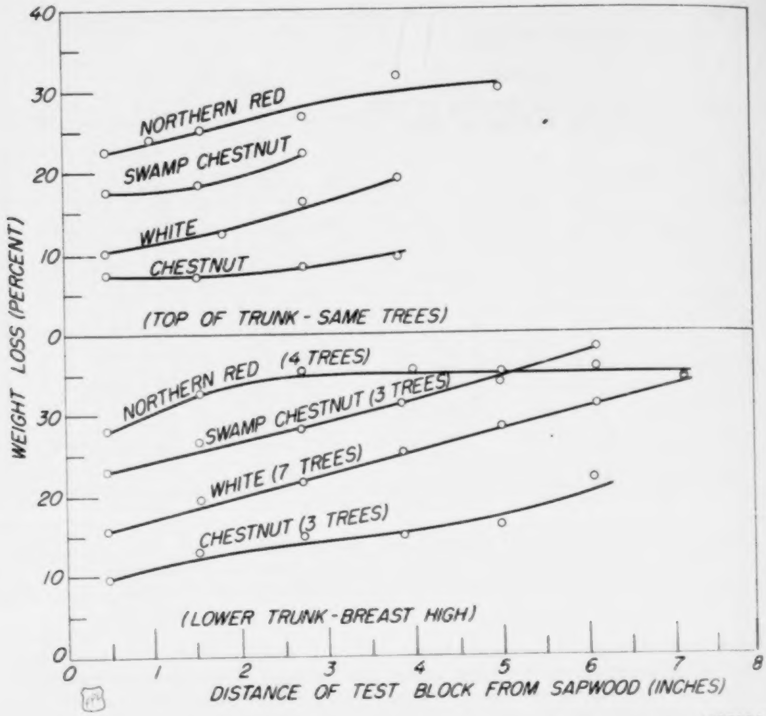

Figure 11-9.—Weight loss in blocks from different parts of individual oak trees. Based on averages for the indicated number of trees and decay caused by *Poria placenta* (as *P. monticola*), *Gloeophyllum trabeum*, and *Xylobalus frustulatum*. (Drawing after Scheffer et al. 1949.)

In a study of red oaks from Alabama, Arkansas, Louisiana, and Mississippi, Toole and Darwin (1970) found no clear differences between decay rates of inner and outer heartwood exposed to *G. trabeum* and *C. versicolor*; oak species studied were water, cherrybark, and southern red. Frequency of tyloses, specific gravity, and pH were negatively correlated to weight loss from *G. trabeum* (a brown-rot fungus), but not strongly enough for precise prediction purposes. Of the variables studied, only fiber length was correlated (negatively) with weight loss from the white-rot fungus *C. versicolor*.

Effect of heat on natural decay resistance.—Heat is required to kiln dry hardwood lumber and veneer, to hot-press glue plywood and particleboards, and to steam bend products such as boat frames. Scheffer and Eslyn (1961) concluded that the effect of such process heat on the decay resistance of mill-run white oak lumber selected to contain only heartwood was minor, although moist heat did slightly reduce decay resistance and the effect was time related. For example, after 24 hours of wet heat (225°F) weight loss was 10 percent more than that for unheated white oak; after 48 hours it was 15 percent more.

11-2 SAP STAINS AND MOLDS[3]

Stain and mold fungi—generally Phycometes or Fungi Imperfecti—feed primarily on contents of cells and do not destroy cell walls. They are confined largely to sapwood and vary in color. The principal fungus stains are usually referred to as "sap stain" or "blue stain." Many molds color only the wood surface, but the distinction is not clear cut. Typical sap stain or blue stain penetrates into the sapwood and cannot be removed by surfacing. In cross section, the discoloration often tends to be aligned radially, i.e., with the wood rays. It may completely cover the sapwood or may occur as specks, spots, streaks, or patches of varying intensities of color. The so-called "blue" stains, which vary from bluish to bluish-black and gray to brown, are the most common; various shades of yellow, orange, purple, and red are sometimes encountered. Stain color depends on the infecting organisms and the species and moisture condition of the wood (see sec. 9-1). The brown stain mentioned here should not be confused with chemical brown stain.

Mold discoloration usually first become noticeable as largely fuzzy or powdery surface growths, with colors ranging from light shades to black. Among the brighter colors, green and yellowish hues are common. On softwoods—though the fungus may penetrate deeply—the discoloring surface growth often can easily be brushed or surfaced off. On hardwoods, however, the wood is commonly stained too deeply to be surfaced off. The staining tends to occur in spots of varying concentration and size, depending on the kind and pattern of the superficial growth.

Under favorable moisture and temperature conditions, staining and molding fungi may invade and develop rapidly in the sapwood of logs shortly after they are cut. In addition, lumber and such products as veneer, furniture stock, and millwork may become infected at any stage of manufacture or use if they become sufficiently moist. Freshly cut or unseasoned stock that is piled during warm, humid weather may be noticeably discolored within 5 or 6 days. Recommended control measures are given in chapter 21.

Stains and molds are not stages of decay; the causal fungi ordinarily do not attack the wood substance appreciably. Ordinarily, they affect the strength of the wood only slightly; their greatest effect is usually confined to strength properties that determine shock resistance or toughness (see sec. 9-1 and chapter 10).

Stain- and mold-infected stock is practically unimpaired for many uses in which appearance is not a limiting factor and a small amount of stain may be permitted by standard grading rules. Stock with stain and mold may not be entirely satisfactory for exterior millwork because the infected wood has greater water absorptiveness. Also, incipient decay may be present—though inconspicuous—in the discolored areas. Both of these factors increase the possibility of decay in wood that is rained on unless the wood has been treated with a suitable preservative.

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[3] Text under this head is based on U.S. Department of Agriculture, Forest Service (1974).

Darkly pigmented fungi in refiner mechanical pulps are sometimes unacceptable, unless bleached; mold and sapstain fungi can therefore cause serious problems unless the raw wood material is protected while in storage. (See chapter 16 for storage procedures for pulpwood.)

11-3 BACTERIAL ATTACK

Bacteria occur frequently in living hardwoods and in hardwood products. Usually they cause no significant problems, but there are some exceptions. Destruction of pectin and cellulose in sapwood by some bacteria (Harmsen and Nissen 1966) can increase permeability enough to cause bleeding in preservative treated wood (Smith 1975). More significantly, bacteria can cause structural changes in red oaks resulting in honeycomb and ring-failure after kiln-drying (Ward et al. 1972). Certain bacteria grow within live trees and in green lumber, where they produce foul-smelling organic acids; Zinkel et al. (1969) found such bacteria in northern red oak, black oak, and water oak. Additionally, mixtures of different kinds of bacteria, and probably fungi also, can accelerate decay of treated cooling tower slats and mine timbers (U.S. Department of Agriculture, Forest Service 1974).

11-4 TREE DISEASES[4]

Hardwoods growing on southern pine sites, like those on better sites, are subject to trunk and root rots, wilts, dieback, declines, and shake. These diseases significantly increase the difficulty of harvesting and utilizing the pine site hardwoods. A detailed listing of pathogens and individual species is given by Hepting (1971) and in the *Index of Plant Diseases in the United States* (U.S. Agricultural Research Service 1960.) Certain fungi prefer top, butt, or root sections; discussion by tree section is therefore useful, although attacks often overlap from one tree portion to another.

Shigo (1979) views tree decay as a four-part system, as follows:

- Wounds start the process.
- Many organisms are associated in tree decay, and successions of organisms are involved in infection of the wood.
- Living tree cells behind wounds react to compartmentalize the injury and infected tissues.
- Discolored and decayed wood results, but is compartmentalized.

Readers interested in studying further this expanded concept of tree decay will find useful Shigo's (1979) generously illustrated publication.

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[4] The text under this section is expanded from DeGroot and McCracken (1977) by permission of the authors and the Forest Products Research Society.

TRUNK ROTS

Decay micro-organisms enter living trees through wounds, fire scars, or broken tops and branch stubs. Because of the high incidence of fire wounds and logging damage near ground level, much trunk rot is initiated as butt rot. Eighty-four percent of southern hardwoods with fire scars more than 2 inches wide develop butt rot (Toole 1960a). Bacteria and nondecay fungi usually invade wounds in northern hardwoods before decay fungi become established (Shigo 1965). A similar succession may occur in southern hardwoods. Spores of *Pleurotus ostreatus* (Jacq. ex Fr.) Quél., which causes rot in oaks, germinate better in the presence of other micro-organisms or the carbon dioxide produced by them than under sterile conditions (McCracken 1974).

A tree's response to a wound tends to confine most decays to the column of wood formed before the injury. In northern hardwoods, wounds stimulate formation of a thin ring of wood tissue with a disproportionately high phenolic and parenchyma cell content. This ring, which may extend many feet above and below the wound, acts as a barrier to most decay fungi and other micro-organisms that gain entry into the trunk (Shigo 1965, 1966). Consequently, decay columns develop within wood formed prior to wounding, but they do not expand centrifugally into wood formed later. In southern hardwoods, this compartimentalization of decay is evidenced by decay columns that extend above fire scars but do not penetrate into wood formed after the burn (fig.11-10). In mature northern red oaks and white oaks with basal fire or mechanical wounds, columns of discolored and decayed wood advance farthest along the sapwood-heartwood boundary present at time of wounding (Shigo 1972a).

Decay fungi of one unique group, the canker rots (Hepting 1971), are not compartmentalized. These fungi grow down old branch stubs into the heartwood, but also spread out from the point of entry to attack cambium and sapwood formed after infection. As the cambium dies, callus folds form, which in turn are killed by the spreading fungus, and progressively enlarging cankers develop.

Discolored wood at the end of decay columns is often infected only by bacteria and nondecay fungi (Cosenza et al. 1970). *Bacillus* and *Pseudomanas* sp. accompany decay fungi in beech (*Fagus grandifolia* Ehrh.), birch (*Betula alleghaniensis* Britton), and maple (*Acer* sp.) (Shigo 1967; Siegle 1967; Cosenza et al. 1970). *Clostridium* sp. and *Bacillus* sp. have been isolated from discolored wood and from shake zones in red and black oaks (Shigo et al. 1971; McGinnes et al.1974).

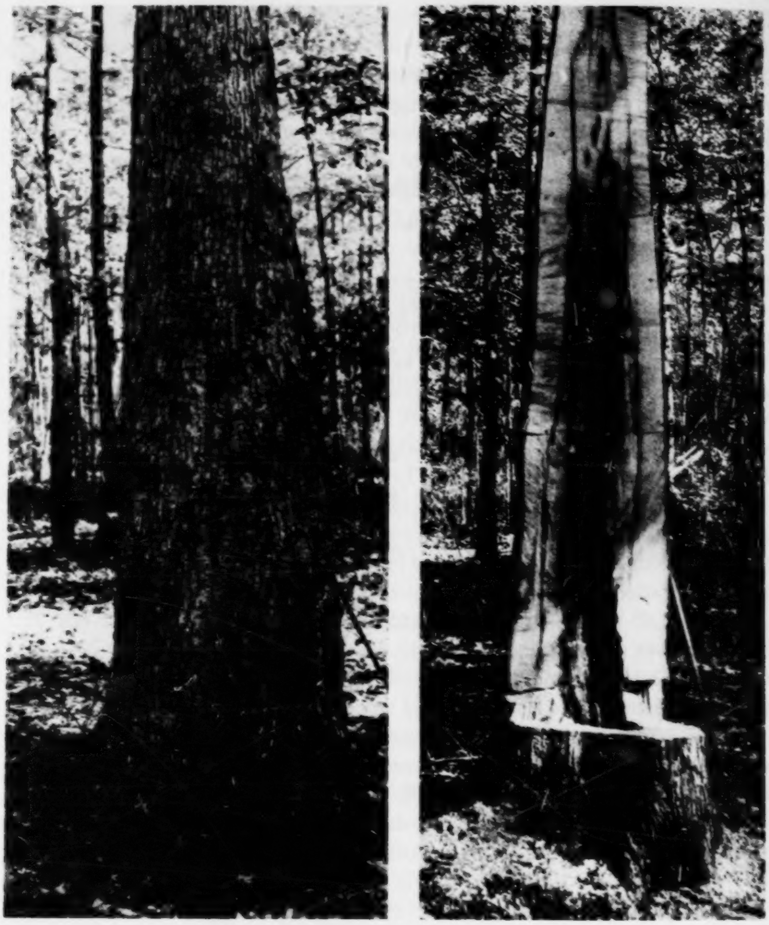

Figure 11-10.—Decay behind fire scar in willow oak (*Quercus phellos* L.) 14 inches in dbh is restricted to column of wood formed before the wound. Wood formed after the wound is not decayed. (Photo from DeGroot and McCracken 1977.)

Five genera of sap-rot fungi appear on exposed white oak, red oak, and water hickory (*Carya aquatica* (Michx. f.) Nutt.) in the Mississippi Delta during the first through third years after scarring: *Stereum, Schizophyllum, Nectria, Nummularia,* and *Polyporus* (Toole 1959). Of the numerous heart-rot fungi which can follow the sap rotters, five caused half the identified cases of decay. These were *Pleurotus ostreatus, Hydnum erinaceus* Bull. ex Fr. (now commonly referred to as *Hericium erinaceus* (Bull. ex Fr.) Pers.), *Polyporus fissilis* Berk & Curt. (*Tyromyces fissilis* (Berk & Curt.)), *P. lucidus* Leys. ex Fr. (*Ganoderma lucidum* (Leys. ex. Fr.) Karst.), and *P. sulphureus* Bull. ex Fr. (*Laetiporus sulphureus* (Bull. ex Fr.) Bond & Sing.) (Toole 1959).

Hackberry is the species most susceptible to decay infection after wounding; oak, ash, sweetgum, and persimmon (*Diospyros* sp.) follow in susceptibility (Hepting 1935). Toole (1959) reported longitudinal decay spread after wounding to be 2.0 feet per decade in overcup oak (*Q. lyrata* Walt.) and sugarberry, 1.6 feet per decade in water hickory, 1.3 feet per decade in red oaks and green ash, and 0.9 feet per decade for sweetgum and elm.

Oaks on southern pine sites are also susceptible to canker rots caused by *Polyporus hispidus* Bull. ex Fr. (*Inonatus hispidus*), *Poria spiculosa* Campb. and Davids, and *Irpex mollis* Berk. and Curt. Cankers from *P. hispidus* lengthen at a rate of 0.5 feet per year, and the length of the decay column exceeds canker length by an average of 2.4 feet (Toole 1955). Rot behind *P. spiculosa* cankers increases in length at about 10 inches per year. With *Irpex* cankers (fig. 11-11), decay usually extends vertically several feet above the canker, tapering to a thin central core. There is apparently no relation between tree vigor and occurrence of *Irpex* cankers (Roth 1950).

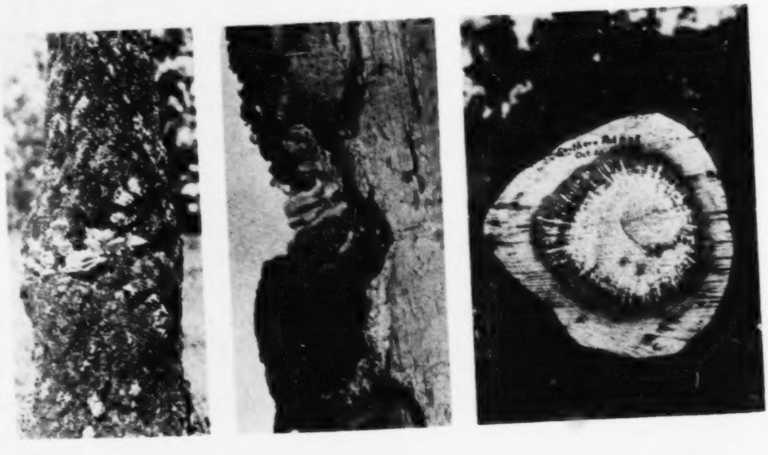

Figure 11-11.—Canker in southern red oak caused by *Irpex mollis* Berk. & Curt. (Left) Fruiting fungi on 8-inch stem. (Center) Longitudinal section showing fruiting and rot. (Right) Cross-section taken 2 feet below the canker, illustrating cylinder of rot with finger-like rotted areas extending to edge of heartwood. (Photos from Roth 1950.)

Site generally does not have a major influence on occurrence or rate of decay in southern hardwoods (Hepting 1935; Roth 1950; Toole 1965; McCracken 1974). Fire history of a stand is more important in determining trunk rot incidence than is site index. Manuals for estimating the amount of chippable cull or sound wood in standing trees have been developed for northern hardwoods (Silverborg 1954; Shigo and Larson 1969) but not for southern hardwoods.

Losses from decay and defects in living trees can be minimized by reducing basal fire scars and logging wounds (Hepting and Kimmey 1949; Toole 1960a; Mobley and Kerr 1973). Felling trees with hispidus canker rot restricts the dissemination of spores to infection sites on nearby trees, even though the fungi continue to sporulate on the felled trees (McCracken and Toole 1974).

Detection of trunk rot.—The most certain indication of trunk rot is the presence of fungus fruiting bodies (fig. 11-12 top left); these occur on the lower trunk, butt, or root zone, but may not be noticed if they are small, short-lived, hidden, or produced either infrequently or after tree death. Other reliable indicators (fig. 11-12) are hollow branch stubs, old wounds—both open and healed, hollows, and abnormal swelling or butt bulge (McCracken 1977). Shigo and Shigo (1974) have described an instrument for detecting decayed and discolored wood in trees and utility poles by determining their patterns of changes in resistance to a pulsed current; an abrupt decrease in resistance, detected in radially-bored, 3-mm holes, indicates the presence of decayed or discolored wood.

Quantitative data on extent of decay.—As noted previously, there are no manuals for estimating the amount of cull and sound wood in standing pine-site hardwoods, but some data helpful to loggers and manufacturers have been published. In the hardwoods, the extent of decay is largely determined by the degree to which they have been wounded during logging operations or scarred by fire.

Considerable data on extent of butt rot such as those of Toole (1959) pertain to flood plains of the Mississippi River. These data are summarized in figures 11-13 and 11-14, because the relationships are probably similar to those for the same species grown on pine sites. The figures are based on data from 1,141 fire-scarred trees dissected in Mississippi and Louisiana. They show that length of heart rot above a fire scar is species dependent and is positively correlated with age of scar, height of butt bulge, height of rotted butt hollow, and diameter of rot showing on the stump. Since quantitative data on hickories and white oaks are scarce, relationships for water hickory (*Carya aquatica* (Michx. f.) Nutt.) and overcup oak (*Quercus lyrata* Walt.) are included.

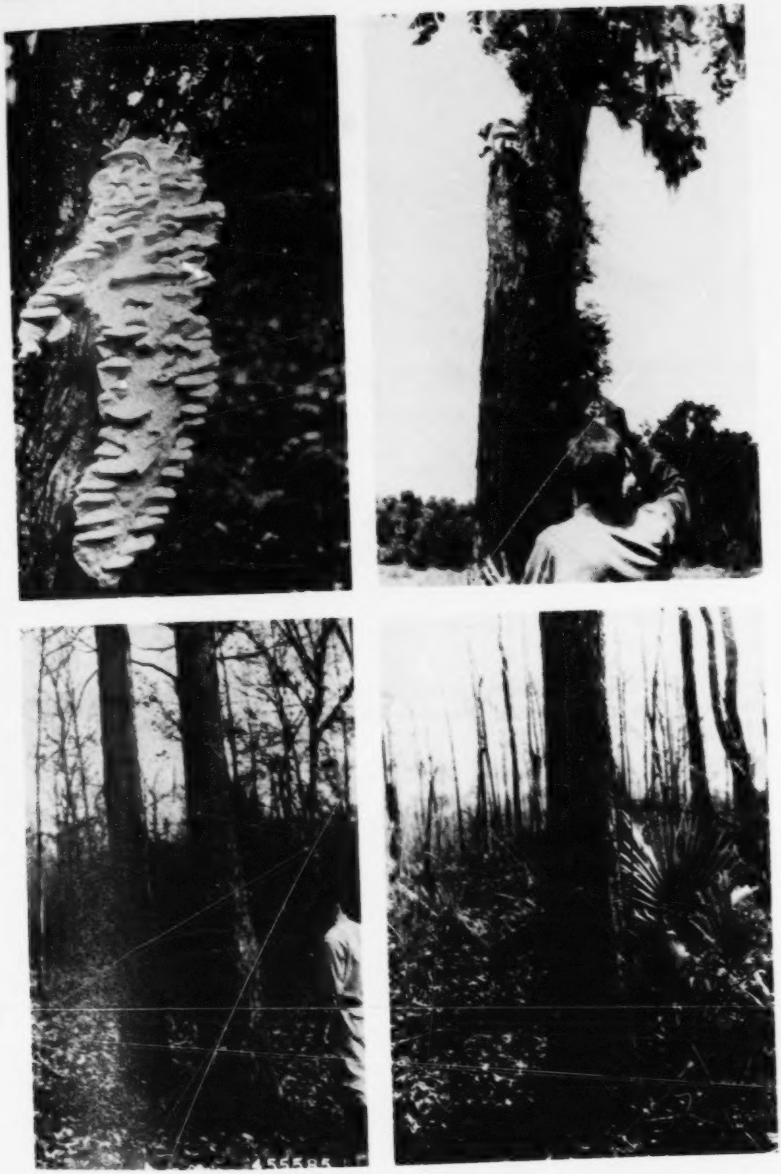

Figure 11-12.—Indicators of trunk rot. (Top left). Fruiting bodies of *Irpex* on a black oak. (Top right). A hollow branch stub. (Bottom left). Butt bulge; stick indicates where tree assumes normal shape. (Bottom right). Fire scar on a 9-inch cherrybark oak; photograph taken 8 years after the fire. (Photos from U.S. Dep. Agric. For. Serv. files.)

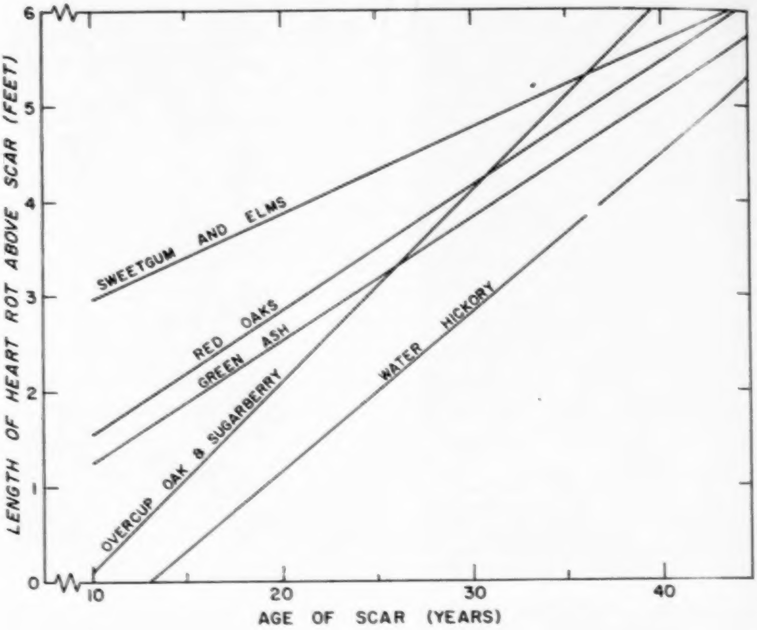

Figure 11-13.—Relation of length of heart rot above original fire scar to age of scar in five species, or species groups, of southern hardwoods. (Drawing after Toole 1959.)

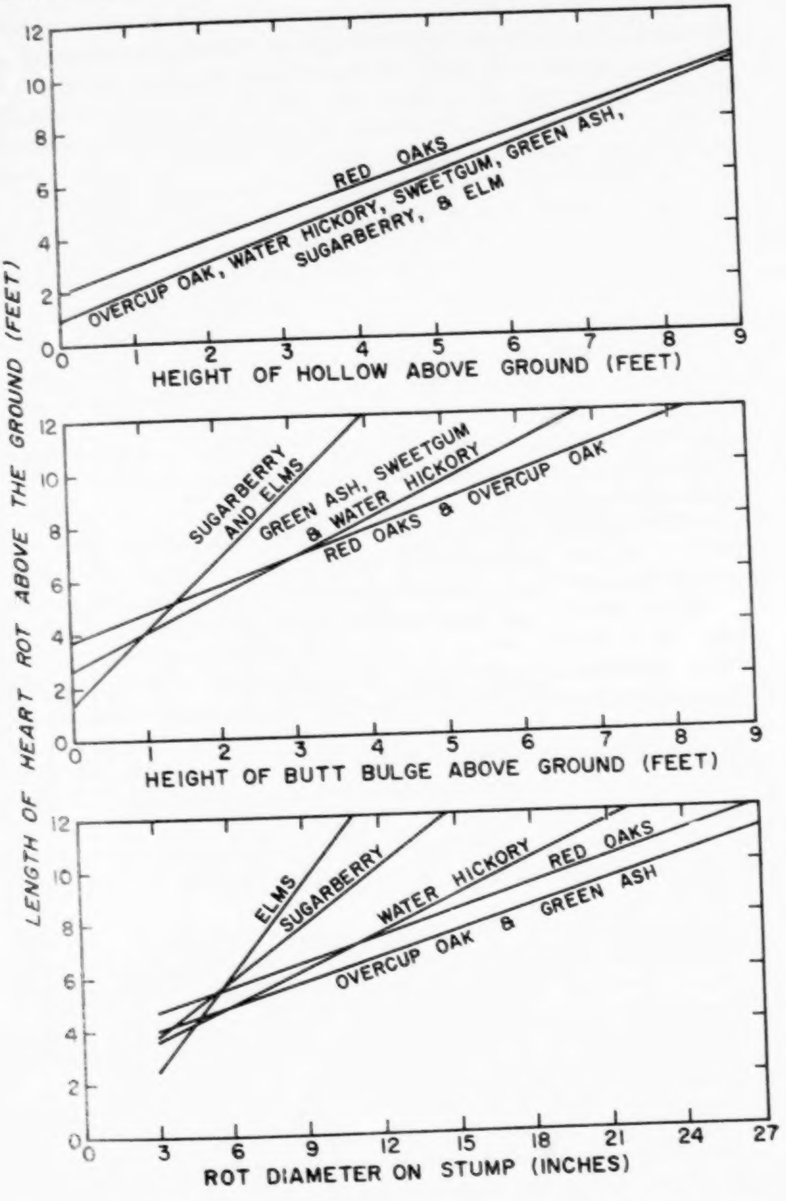

Figure 11-14.—Relation of length of heart rot to height of hollow, height of butt bulge, and rot diameter on the stump in five species, or species groups, of southern hardwoods. (Drawing after Toole 1959.)

Hepting (1935) dissected 602 fire-scarred trees of nine species of Delta hardwoods and analyzed them for extent of decay. The trees were between 3 and 11 inches in dbh and were sampled in Louisiana and Mississippi. He found that fire scars healed most rapidly in the oaks and sweetgum, followed by ash, hackberry, and persimmon. The greater the number of years since scarring, the greater the proportion of scarred trees decayed. Of the species studied, hackberry was found to be the most susceptible to initial infection, followed by the oaks, ash, sweetgum, and persimmon. Following scarring of sweetgum and persimmon, wound gum, produced just under the scarred surface, protects the trees against infection. Much of this protective effect is lost, if subsequent fires kill the exposed sapwood. Hepting's 1935 data indicated that decay spreads upward from the fire scar most rapidly in the oaks (2.3 inches per year), followed in order by ash, sweetgum, hackberry, and persimmon. A positive relationship was found between the rate of decay and each of the following factors: age of tree, percentage of tree circumference scarred, diameter at the time of scarring, and present diameter. Basal breakage of young trees, because of decay following fire-scarring, was infrequent and confined chiefly to overtopped, poor-vigor trees.

In **ash,** Hepting (1935) found that decay spread upward from fire scars at about 1.5 inches per year and that trees in the Delta had fire scars averaging 2.2 feet in height; total height of the decay column after 20 years averaged, therefore, about 5.2 feet. In one fire-scarred ash stand, many of the larger trees were broken over at the base, and the remainder were practically worthless as a result of decay following scarring. Toole's (1959) data on green ash indicate length of heart rot above fire scar after 20 years to average about 2½ feet (figs. 11-13 and 11-14).

While **hackberry** is readily susceptible to infection, decay in this species spreads very slowly up the bole. Hepting (1935) found that height of decay in hackberry 8 years after fire scarring was about 1 foot; 32 years after scarring, decay height was only 1.5 feet. Toole's (1959) data for **sugarberry** show a more rapid spread of decay—to about 4 feet above a fire scar after 30 years (figs. 11-13 and 11-14).

Campbell and Verrall (1956), in their discussion of fungus enemies of **hickory,** note that in 1933 loss due to cull from decay in hickory of sawlog timber size was estimated at 13 percent, and that principal wood-rotting fungi in the South are *Fomes marmoratus* (Berk. and Curt.) Cke., *Fomes densus* Lloyd, *Poria andersonii* (Ell. & Ev.) Neuman, and *Poria spiculosa* Campbell and Davidson—the latter causing cankers.

More recently, Berry and Beaton (1972) found that most decay fungi cause little, if any, decay in hickory trees up to 100 years old and not over 11.5 inches in dbh; no decay was found in trees under 50 years old sampled in the central States. Toole's (1959) data on water hickory from bottomland sites indicate that in this species butt rot progresses more slowly than in most other southern hardwoods (figs. 11-13 and 11-14).

Gruschow and Trousdell (1959) found that amounts of rot in 100-year-old pine-site hardwood sawtimber measuring 10 to 18 inches in diameter varied with species from 4 to 38 percent of sawtimber volume of all trees of the species in the stand; at time of hardwood harvest in the Virginia stand studied, the dominant trees were 100-year-old loblolly pine. Their data are summarized as follows:

Species or species group	Number of trees with rot	Volume deduction due to rot
	Percent	
Yellow-poplar	16	4
White oak	21	4
Other oak (i.e., southern red, black, scarlet, water, and willow)	19	7
Sweetgum	13	5
Tupelos (i.e., black, swamp, and water)	30	13
Red maple	57	38

Few data are published on the progression of heart rot in **elms;** Toole's (1959) data indicate that length of heart rot above fire scar in this species group averages about the same as sweetgum, i.e., about 4 feet after 20 years (figs. 11-13 and 11-14).

Data on the extent of rot in pine-site **red maple** are limited to those of Gruschow and Trousdell (1959), just cited, that indicate 38 percent cull volume due to rot at age 100.

More data are available on the extent of decay in **oaks** than in other hardwood species, but information is far from complete. Hepting's (1941) study of white oak, chestnut oak, northern red oak, black oak, and scarlet oak sawlogs from the Appalachians (northern Georgia to northern Virginia) showed that board-foot volume of cull in the 16-foot butt log of these species can be predicted from width of basal wounds 12 inches above ground and the number of years since the fire (fig. 11-15). Hedlund (1959) found that percent of cubic foot cull in butt logs of red and white oaks varied from 3.7 to 34.0 percent depending on fire scar severity (table 11-2).

TABLE 11-2.—*Percent cull related to fire scar severity in 16-foot butt logs of small- to medium-size sweetgum, white oak, and red oak sawtimber sampled in Louisiana and Mississippi* (Hedlund 1959)

Vertical extent of scar (feet)	Open scars		Closed scars	
	Board feet cull	Cubic feet cull	Board feet cull	Cubic feet cull
	Percent			
0.1-3.0	21.6	13.9	6.5	3.7
3.1-9.0	40.4	24.3	19.8	12.4
9.1-17.3	59.0	34.0	34.9	17.1

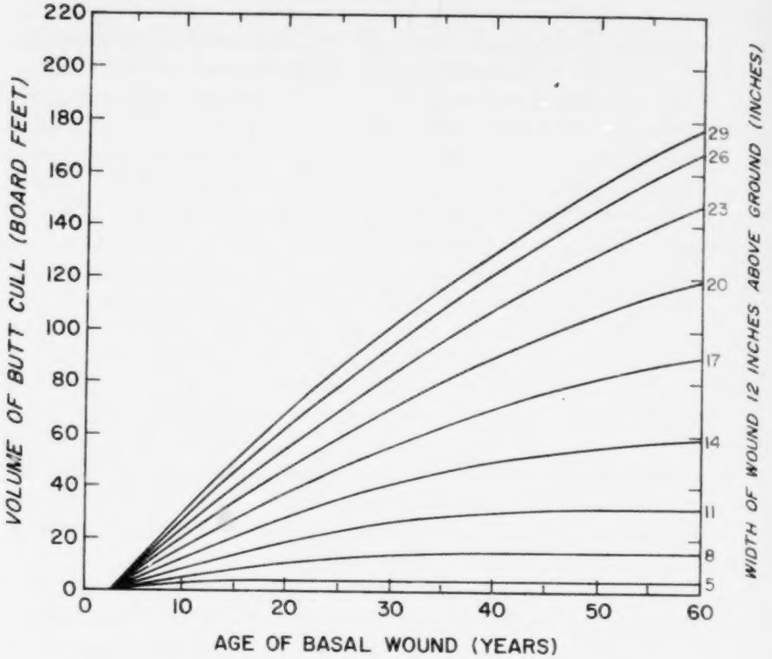

Figure 11-15.—Relation of cull volume in 16-foot butt logs to age of basal wounds for different wound widths. The curves are based on old-growth oaks (white, chestnut, northern red, black, and scarlet) from the Appalachian Mountains. (Drawing after Hepting 1941.)

Berry and Beaton's (1971) study of 114 northern red oaks (5.6 inches dbh and larger) from Virginia, Kentucky, Ohio, Indiana, Illinois, and Missouri indicated that decay is not serious in this species for the time necessary to produce high-quality saw logs and veneer logs. In 30 to 90 year-old trees about one percent of cubic volume was decayed; trees 91 to 130 years old averaged 3.3. percent in decayed volume. Over half of this decayed volume was in fire-scarred trees.

Burns (1955) studied 53 black oaks, 53 scarlet oaks, and 42 white oaks 9 inches dbh and larger randomly selected from two sites in Missouri; the black and scarlet oaks averaged 12 inches dbh and 45 years, the white oaks 14 inches dbh and 75 years of age. For all species, fire scars were associated with more than half the cull, and almost 90 percent of the cull in scarlet was associated with fire scars (table 11-3). In scarlet and white oaks, an open fire scar from an old wound generally indicated that the tree was a cull for lumber production. Rot from visible fire scars extended an average of 3 feet above the stump in black oak, 5 feet in white oak, and 9 feet in scarlet oak. Decay after wounding had spread upward at 1 to 2 inches per year. Fire wounds healed more slowly on white oak than on black and scarlet oaks. On average, it took 6 years for wounds on black and scarlet oak to heal, 17 years for white oak wounds.

TABLE 11-3.—*Cull percentages, defective and sound trees combined, for three species of oak grown in Missouri* (Data from Burns 1955)[1]

Wound type	Oak species		
	Black	Scarlet	White
	Percent of board foot volume		
Fire			
Visible fire scars	5.3	9.7	4.4
Hidden fire scars	1.4	1.7	2.1
Total fire cull	6.7	11.4	6.5
Branch stubs	1.8	1.0	4.2
Insect holes	2.1	.4	.9
All types combined	10.6	12.8	11.6

[1] Trees were 9 inches or larger in dbh. Scarlet and black oak averaged 12 inches dbh and 45 years of age; white oak trees averaged 14 inches dbh and 75 years old. Logs from the merchantable stem were scaled by the International 1/4 rule, and deductions for scalable defect or cull were made.

Hepting and Hedgecock (1935a) provided data on the cull percentage in oaks up to 34 inches in diameter sampled from North Carolina north to New Jersey. The cull percentages, based on Scribner Decimal C log rule for merchantable boles of trees in size classes and species of interest, are abstracted as follows:

Tree species	Tree dbh, inches			
	10	12	14	16
	Percent cull			
Scarlet oak	6	8	10	12
Post oak	—	10	9	10
Black oak	—	6	7	7
Northern red oak	3	4	6	8
White oak	4	3	4	6
Chestnut oak	3	2	5	8

The foregoing tabulation reflects the mix of trees with and without fire scars as they naturally occurred in 1935. When their data are arranged to show the relationship of cull percentage to frequency of fire scars, the detrimental effect of fire on hardwoods is more apparent (fig. 11-16).

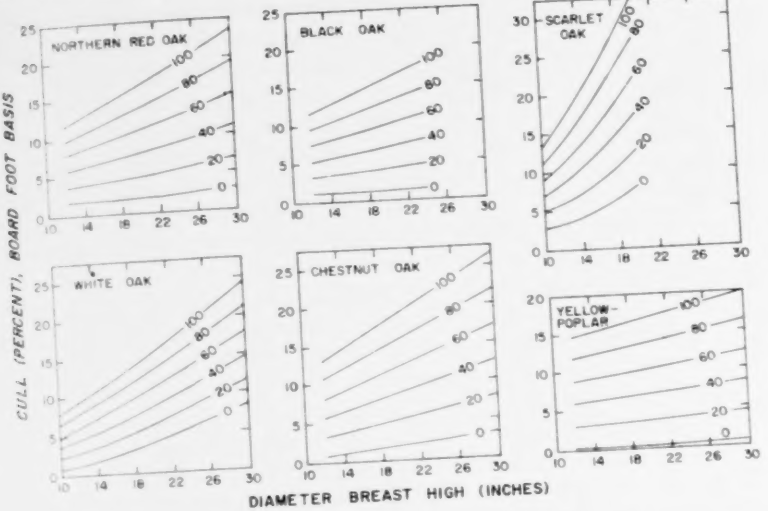

Figure 11-16.—Relation of cull percent to tree diameter and percentage of trees with basal wounds (100, 80, 60, 40, 20, and 0 percent) for five oak species and yellow-poplar sampled from North Carolina to New Jersey. The cull is expressed as a percentage of the Scribner Decimal C log scale of merchantable boles. Graphs are based only on trees regarded as merchantable when cut in 1935. (Drawing after Hepting and Hedgcock 1935b.)

Butt rot makes up only about half the loss from decay in standing oak timber of merchantable size. The other half of the rot cull originates higher on the trunk or in the top. Knowledge of top rot is needed by cruisers assessing value of stands and by foresters choosing good risk trees for future growth. Hepting et al. (1940) analyzed **top rot** in 333 oaks of five species (white, chestnut, northern red, black, and scarlet) on ten commercial logging operations extending from northern Georgia to Virginia. Features associated with major decay, aside from fruiting bodies of fungi (conks), were broken main stems and major limbs, rotten branch stubs 3 inches or more in diameter a few inches from the bole, large surface injuries generally a square foot or more in extent, open holes, and blind (i.e., overgrown) knots. Any oak with the top broken out, with a hole in the bole, or bearing a conk is likely to be largely cull. Major findings of Hepting et al. (1940) are summarized in figure 11-17. Their study included only 18 scarlet oaks, and they concluded it likely that the amount of top rot cull in scarlet oak generally exceeds the amount shown in figure 11-17 for the different risk classes. They further concluded that timber markers should leave for future cuts only oak trees of risk class A (possibly risk class B also) to minimize cull.

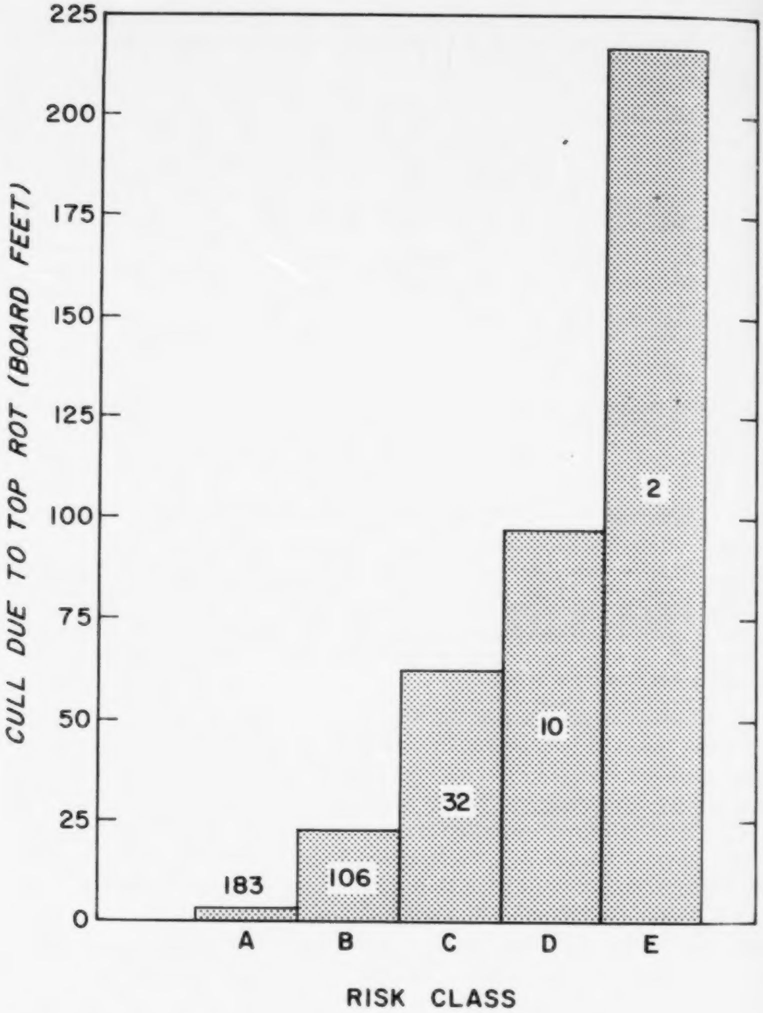

Figure 11-17.—Cull per tree due to top rot in five species of Appalachian oaks (white, chestnut, northern red, and scarlet) according to five risk classes defined as follows (numbers inside the bars indicate the number of trees upon which each bar is based): (A) No rotten stubs over 3 inches thick, no large surface wounds, no holes, and less than three blind knots or healed stubs, anywhere on the bole up to 8 feet above merchantable top. (B) One rotten stub or large surface wound, or three blind knots. (C) Two rotten stubs or large surface wounds, or four to five blind knots and stubs. (D) Three rotten stubs or large surface wounds, or six to seven blind knots and stubs. (E) Four or more stubs and wounds or eight or more blind knots and stubs. (Drawing after Hepting et al. 1940.)

In sweetgum Hepting (1935) found that 8 years after an initial fire, 42 percent of trees with only one fire scar had butt rot; those that had second and third fire scars incurred in the 8-year period had nearly double the incidence of butt rot (79 percent). In these sweetgums, decay spread slowly up the bole from fire scars—at a rate of about 1.2 inches per year. Data on volume loss in sweetgum are scarce. Lentz (1929) reported a loss of 15 percent of merchantable volume in a Louisiana stand harvested in 1928 following burns in 1916 and 1924. Gruschow and Trousdell (1959) reported only 5 percent of volume lost due to rot in 100-year-old pine-site sweetgum. Proportions of 16-foot butt logs culled for rot in Mississippi and Louisiana fire-wounded sweetgum trees of small to medium sawtimber size were reported by Hedlund (1959) to range from 3.7 to 34.0 percent of cubic content (table 11-2) depending on vertical extent of scar and whether the scar was open or closed. Factors affecting length of heart rot columns above fire scars in sweetgum are graphed in figures 11-13 and 11-14.

No data are available for **tupelo** except those of Gruschow and Trousdell (1959) who found that 100-year-old black, swamp, and water tupelos growing under dominant loblolly pine in Virginia had 13 percent cull volume due to rot.

Information on decay volume in **yellow-poplar** is also scarce. In the Virginia stand just mentioned, 100-year-old yellow-poplar had only 4 percent cull volume due to rot. Hepting and Hedgecock (1935b) found such low rot volumes only in trees unscarred by fire; fire-scarred yellow-poplar in the Appalachians had 15 to 20 percent cull due to rot, depending on tree diameter (fig. 11-16).

Wound dressings and pruning.—Because cull from wound-related decay is so extensive in southern hardwoods, pruning techniques and the effectiveness of wound dressings have been the subject of considerable research. Opinions on these subjects are not unanimous.

Roth (1939, 1948) proposed special training for pruning crews and made the following comments on pruning oaks. Exposed tissue around wounds made during the early growing season does not die back as much as tissue around wounds made at other seasons of the year; however, there is greater danger of loosening the bark around the wounds. Wound width is a better criterion for measurement of pruning wounds than an average of width and length, since the width of a wound rather than its length determines healing time. Season of pruning has little or no effect on healing where bark stripping or other injuries causing excessive dieback at the sides of the wounds are kept at a minimum. The more vigorous the tree and the pruned branch, the more rapid the healing.

Pruning of white oak is of doubtful value in thinned or open stands since water sprouts develop profusely on the boles of the pruned trees. Wounds wider than 1.5 inches may result in decay. Discoloration, while common in all sizes of pruning wounds, was not very extensive. The extension of both decay and discoloration was greater downward than upward. In pruning dead branches, the cut should be made through the living callus at the base of the branch so as to promote rapid healing. In removing live branches, a flush cut should be made, and care should be taken not to strip the bark below the cut. A ladder and a handsaw are recommended for oak pruning where the stands are not too dense. Live branch pruning on young vigorously growing oaks not over 5 inches dbh will result in quick healing, prevent loose knots, and provide a maximum of clear length and a minimum of rotten knots and heart rot.

Grano (1957) found that 5 years after pruning southern red oak averaging 6.4 inches dbh, 85 percent of the wounds had healed over completely. Originally the wounds averaged 1.2 inches in diameter, ranging from 0.4 to 3.6 inches. They did not serve as an important entrance for rot.

In a series of studies dealing with treatments to promote healing of tree wounds in southern hardwoods, McQuilkin (1950) found that, except for red maple, wounds made in late winter or early spring healed faster than those made at other seasons. Because of excessive bleeding in early spring, wounds on red maple healed best if made in late spring or early summer. McQuilkin concluded that lanolin proved to be consistently effective as a wound-dressing material. Shellac and growth regulators did not promote healing of wounds.

Shigo and Wilson (1972) wounded 60 red maple trees in New Hampshire and 25 elms in Ohio and then treated the wounds with an asphalt dressing, with orange shellac, and with a polyurethane varnish. Bacteria and fungi invaded all wounds. Wound dressings had no effect on invasion by microorganisms or on the processes of discoloration after 1 year.

ROOT ROTS

Harvesting of stumps and central root mass of pine-site hardwoods (figs. 14-4 through 14-26, and 16-32) for energy wood or chemicals may be economically feasible in the future. Rot-infested roots and stumps in which both heartwood and sapwood are attacked will be difficult to harvest, however, because roots so infected will easily break and remain in the soil when trunks are pulled from the ground.

Some root-rot fungi that attack hardwoods can also infect subsequently planted pines. Two pathogens which exemplify this potential are *Clitocybe tabescens* (Scop. ex Fr.) Bres. (*Armillariella tabescens* (Scop. ex. Fr.) Sing.) and *Corticium galactinum* (Fr.). Burt. (*Scytinastroma galactinum* (Fr.) Donk).

Clitocybe tabescens causes root rot of elm, hickory, red maple, sweetgum, oaks, and over 200 other species in the South (Rhoads 1950, 1956; Filer and McCracken 1969). It is a saprophyte in stumps and frequently becomes parasitic on living trees. A general decline in tree vigor is usually accompanied by a yellowing of leaves, which fall prematurely or remain small and scant. All foliage may die simultaneously on small trees. White, fan-shaped mycelial fungus mats occur between root bark and wood at the root collar, and may extend upward into the stem. Both heartwood and sapwood become light yellow to white and soft as decay advances (Rhoads 1956). Yellow-brown mushroom clusters develop near the ground in advanced disease stages.

A white root rot results from attack by *Corticium galactinum* on northern hardwoods and conifers (White 1951). It also attacks black oak and other *Quercus* species in the Ozarks (Von Schrenk and Spaulding 1909). In Arkansas, most affected trees were from 2 to 10 inches dbh and were growing on poor white oak sites; there was evidence of tree-to-tree spread (Toole 1960b). Sweetgum, white oak, sycamore (*Platanus occidentalis* L.), and Nuttall oak *Q. nuttallii* Palmer) are also susceptible. Green ash and water oak are less susceptible, but some trees can be killed (Toole 1967).

A white or cream-colored layer of fungus mycelium frequently appears on root surfaces below the soil. Liberated spores are wind-disseminated. They germinate and invade dead woody tissue. Mycelium then can directly invade healthy roots of nearby coniferous or broadleaf trees.

In general, there is no practical control of these root diseases. Fungi in old roots and debris that remain in the soil serve as primary inoculum to either conifers or broadleaf seedlings for several years. Infection of healthy trees apparently occurs when their roots come in contact with infested wood (old roots, etc.) in the soil. Replanting pines in areas where diseased trees exist seems impractical as only 50 percent may survive (Clayton 1953).

WILTS, DIEBACKS, AND DECLINES

Sweetgum blight has been common throughout much of the sweetgum range since 1950 (Garren 1949; Miller and Gravatt 1952; Toole 1960c). Oak wilt, caused by *Ceratocystis fagecearum* (Bretz) Hunt, occurs in 21 states but is most common in a central area from the eastern edge of the Great Plains to the Appalachian Mountains with a southern boundary across Tennessee and northern Arkansas (Jones and Phelps 1972). All oaks and some species of *Castanea* and *Castanopsis* are susceptible (Hepting 1955; Jones and Phelps 1972). Dutch elm disease caused by the fungus *Ceratocystis ulmi* (Buism.) C. Moreau has been recorded in most states east of the Mississippi and has slowly progressed westward. All native elms are susceptible (Banfield 1968).

Another threat in the Southeast is a wilt disease caused by *Cephalosporium diospyri* Crandall (Toole and Lightle 1960). *C. diospyri* causes persimmon wilt (Crandall and Baker 1950; Wilson 1963) and attacks willow oak (*Q. phellos* L.) post oak, Texas red oak (*Q. shumardii* var. *texana* (Buckl.) Ashe), winged elm, and hackberry (Bush 1973). It is also implicated in disease complexes causing mortality and decline of live oak (*Q. virginiana* Mill.) (Van Arsdel and Halliwell 1970) and sycamore (Lewis and Van Arsdel 1975).

Wood of wilt-killed trees is not usually directly affected by the tree-killing pathogen, except for narrowed outer annual rings. Sapwood-rotting fungi promptly attack when trees die, however. As long as the bark remains intact on dead trees, wood moisture content will support sap-rotting fungi (Lindgren and Eslyn 1961).

Phloem necrosis of elms, probably caused by a mycoplasma (Wilson et al. 1972; Filer 1973) is widespread in the Midwest and extends further south than does Dutch elm disease (Swingle et al. 1949). Superficially, the disease resembles a wilt or decline. Similarly, the wood is not directly affected by the pathogen (McLean 1944).

SHAKES

In terms of loss on conversion, **shake**—a separation of annual growth sheaths arising from non-pathogenic causes—is a severe defect. Shake can be present in standing trees without external indicators. Thus, the logger is unable to exclude shake-defective trees from his cut, and affected lumber could proceed through seasoning and manufacture before ring shake becomes apparent in finish application. Tree species vary in their susceptibility to shake. In Missouri, McGinnes (1965) found white oaks more shake-free than either black or red oaks.

In northern hardwoods, shakes were associated with wounds on trunks and below the root collar (Shigo 1972b). Shakes may develop between normal xylem tissue, formed before a wound, and wound-response tissue, formed after the wound but still within the same year's growth increment (McGinnes 1974). They occur most frequently in the latewood or at the latewood-earlywood interface (McGinnes et al. 1974).

The shake failure in scarlet oak occurs predominantly between cells as opposed to a tearing of the cell wall structure (Kandeel and McGinnes 1970). This failure within the middle lamella zone is caused by either biological degradation or arrested development (polymerization) of the lignin in the middle lamella region of the shake zone (McGinnes and Wu 1973). The shake zone in one scarlet oak was characterized by higher extractives content, higher lignin and methoxyl contents, lower holocellulose content, and lower depolymerization (DP) of the holocellulose fraction than those in normal wood zones (McGinnes and Wu 1973)

11-5 DECAY OF LOGGING SLASH

Under the present methods of logging hardwoods in the South, considerable topwood is left on the site (fig. 11-18). Much of this could be used as pulpwood and dimension bolts, or as fuel wood, if salvaged before it deteriorates. Future demand for wood will probably justify much more complete harvest of hardwood slash; data on rates of slash deterioration indicate how promptly the usable tree parts must be salvaged. Toole's (1965) study of 1,155 tops 13 to 18 inches in diameter at the butt end provides such data on ash, elm, hickory, oak, sugarberry, and sweetgum in Arkansas and Mississippi. The branches on these tops often extended 50 feet or more horizontally and 15 to 20 feet vertically. Toole analyzed the deterioration (figs. 11-19 and 11-20) of components of the slash annually, for seven years following harvest. His conclusions are summarized in the following paragraphs.

PROGRESS OF DECAY

One year after cutting.—From 0 to 17 percent of the leaves remain on the non-oaks, 55 to 100 percent on the broad-leaved red oaks (fig. 11-18), 0 to 10 percent on the narrow-leaved water and willow oaks, and 35 percent on the white oaks. The tops have not compacted, and the bark is largely sound. Less than 10 percent of the twigs, branches, and wood have decomposed. Sap rot is about 0.25 inch deep. Fruiting bodies of fungi are common on red oaks only.

Two years after cutting.—Less than 10 percent of the leaves remain on the oaks, except that southern red oak still retains 40 percent (fig. 11-18). Water hickory retains 2 percent of its leaves, and other species none. Most of the tops have started to compact; their average heights have decreased from 0 to 50 percent. Bark is 65 percent or more sound. Fifty percent of the twigs have fallen to the ground, and 25 percent of those on the ground have decomposed. Sap rot is about 2 inches deep, and fungus fruiting bodies are common.

Three years after cutting.—All leaves have fallen and the tops have compacted (fig. 11-18). The bark has many cracks and loose pieces. In some places most of it has fallen off. Only 20 percent of the twigs remain in the air, and 54 percent of those on the ground have disintegrated.

Four years after cutting.—Six percent of the twigs, 18 percent of the small branches, 46 percent of the large branches, 68 percent of the small wood, and 76 percent of the large wood originally in the air still remain.

Five years after cutting.—No twigs remain in the air, and 27 percent remain on the ground.

Six to seven years after cutting.—No small branches, 2 to 10 percent of the large branches, and about 15 percent of the wood remain in the air. Twenty percent of the twigs, 30 percent of the small branches, and 50 percent of the large branches and wood remain on the ground undecomposed (fig. 11-20).

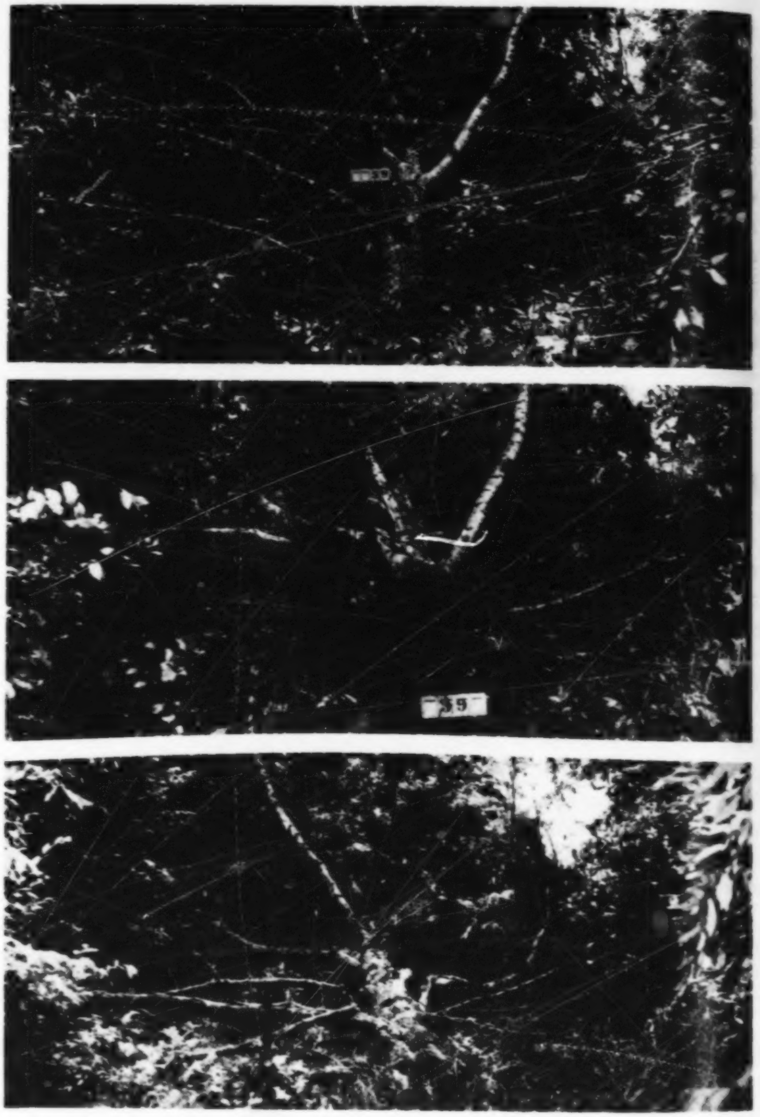

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Figure 11-18.—The top of a southern red oak felled in August 1957, near Vicksburg, Mississippi. (Top) Ten months after cutting the leaves are still attached and the bark is intact. (Middle) After 2 years some leaves are still present, but the bark is cracked and fungi are fruiting. (Bottom) After 3 years no leaves remain and many of the large limbs are broken. (Photo from Toole 1965.)

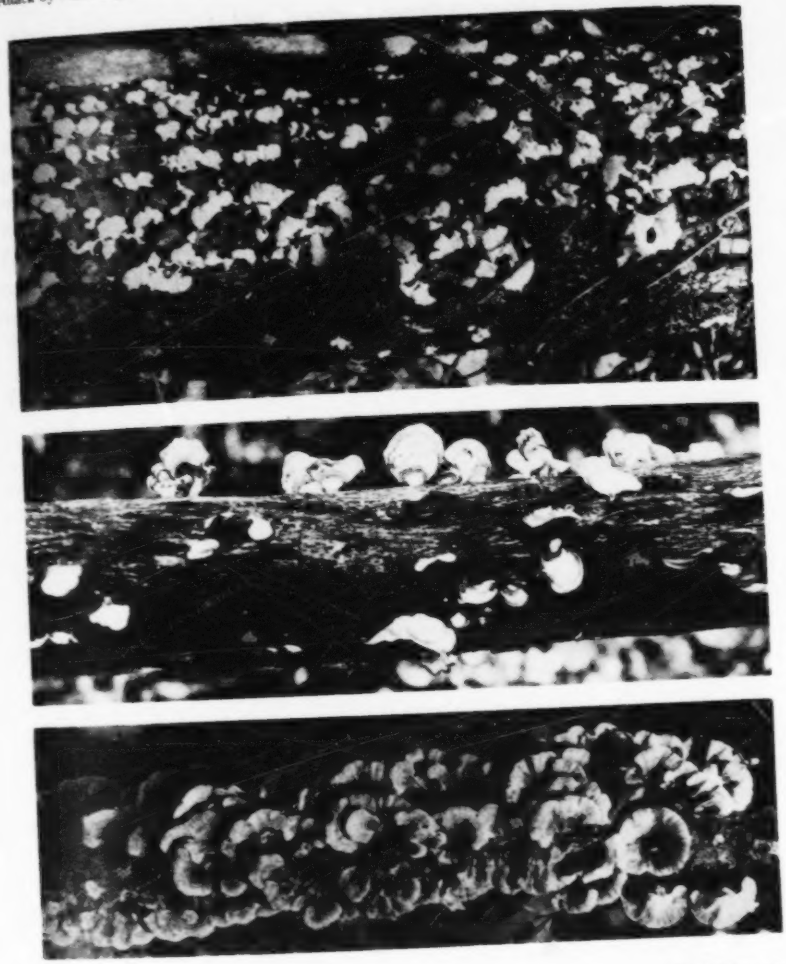

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Figure 11-19.—Sporophores of three fungi common on hardwood logging slash in the South. (Top) *Schizophyllum commune* (Fr.) on persimmon. (Middle) *Stereum ostrea* (Blume & Nees) Fr. on a red oak. (Bottom) *Polyporus versicolor* (L.) Fr. on a red oak. (Photo from Toole 1965.)

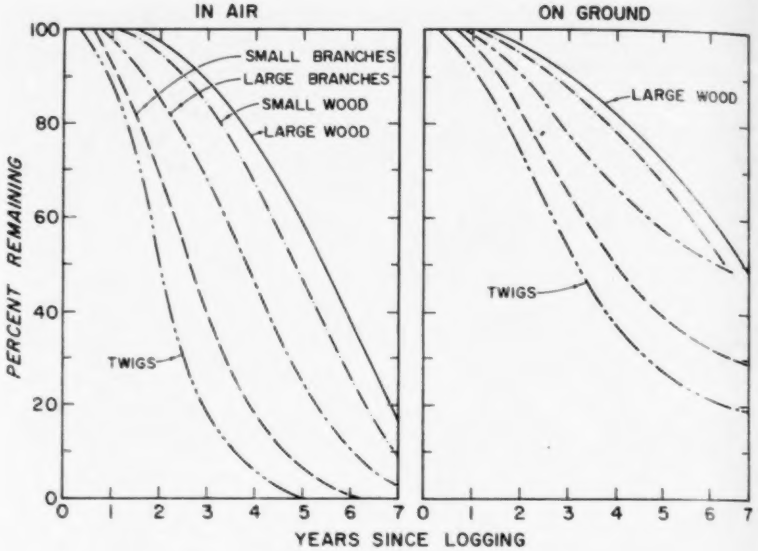

Figure 11-20.—Components of logging slash remaining after trees were cut. Changes with time reflect both disappearance and movement to ground as decay progressed. Species included to derive averages are red oaks, white oaks, hickories, sugarberry, elms, green ash, sweetgum, and honeylocust (*Gleditsia triacanthos* L.). (Drawing after Toole 1965.)

RELATION OF DETERIORATION TO USE

Hardwood topwood cut in the fall sustains no important deterioration throughout the following winter. Thus the sapwood of tops cut in October is largely usable up to 6 months after cutting, although about 35 percent of the volume is stained. Sapwood of spring-cut trees will be cull within 2 months, when 60 percent will be stained and decay will be active. Heartwood usually remains usable and relatively unstained about 2 months longer than the sapwood. Stain coloration alone is not a serious defect, but simultaneous initiation of decay diminishes strength properties of the wood.

The rapid increase of stain and rot in the spring starts from 4 to 6 weeks sooner in fall-cut than in spring-cut tops. Probably fungi become established during the winter but develop rapidly only when temperatures rise in spring. Because of rot, the sapwood is worthless 8 months after fall cutting—40 percent or more of its volume can be expected to be punky. Three months after spring cutting, more than 50 percent of the sapwood is rotten. Heartwood decays more slowly, being about 20 percent and 40 percent rotten 11 months after fall and spring cutting, respectively. Generally, topwood should be salvaged within 6 months and usually has little value after 1 year.

11-6 STAIN, DECAY, AND BACTERIA IN PRODUCTS[5]

As observed in section 11-4, heartwood of almost all the pine-site hardwoods is susceptible to decay (tabel 11-1), and the sapwood of all will stain and decay unless protected. Discolorations in stems, logs, and veneer of pine-site hardwoods are described in chapter 9 under the section head DISCOLORED WOOD. Chapter 16 describes storage procedures, and chapter 21, protective treatments. The following subsections describe deterioration of unprotected roundwood, pulpwood chips, hogged fuel, lumber, composite products, and wood in use; results of efforts to slow deterioration are also described.

ROUNDWOOD[6]

Typical heart-rot fungi within boles of standing trees are not important decayers of logs. Canker rots can attack the sapwood, but most decay in stored logs results from white-rot fungi invading after felling.

Deterioration rates have not been established for ricked hardwood logs as they have been for southern pines (Lindgren 1953); but sapwood in tops of fall-cut trees is largely usable for up to 6 months. Spring- and summer-cut material in the Mid-South cannot be stored for 2 months without substantial deterioration (Toole 1965).

Strawpiled red oak and gum (black tupleo and sweetgum) pulpwood bolts stored on a 2-month rotation in Georgia lost 3 to 4 percent of their specific gravity in summer and negligible amounts during the other seasons (Ference and Gilles 1956). Logs stored on a 5-month rotation lost 6 to 10 percent of their specific gravity in spring and summer and 3 to 4 percent in winter. Burst and breaking strength of pulp from furnish that had lost 13 percent in specific gravity were not seriously affected, but tear strength dropped about 20 percent. Screened yield of oak dropped 0.34 percent with each 1-percent drop in specific gravity.

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[5] The text under this section is taken—with some additions—from DeGroot and McCracken (1977) by permission of the authors and the Forest Products Research Society.

[6] Pesticide and fungicide precautionary statement: This publication reviews research involving pesticides and fungicides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of pesticides and fungicides must be registered by appropriate State and/or Federal agencies before they can be recommended. The list of registered chemicals varies from time to time; prospective users, therefore, should get current information on registration status from Pesticides Regulation Division, Environmental Protection Agency, Washington, D.C. CAUTION: Pesticides and fungicides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife—if they are not handled or applied properly. Use all pesticides and fungicides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and fungicides and their containers.

Decay of hardwood logs has been prevented in the South with chemica treatments, but environmental considerations may restrict this practice today Between March and November, chemical sprays must be effective against bot insects and fungi and must be applied over the entire log (Scheffer and Lindgre 1940). The principal fungicide has been pentachlorophenol in oil or its sodiur salt (sodium pentachlorophenate) in water solution.[6] The insecticide has bee benzene hexachloride (Scheffer 1969).[6]

Logs can be successfully protected from stain and decay in the South by wate sprinkling (Carpenter and Toole 1963; Djerf and Volkman 1969). Intermitter sprinkling (12 hours on and 12 hours off) was nearly as effective as continuou sprinkling in protecting hardwood logs during 16 summer weeks (Carpenter an Toole 1963). Under intermittent spray, hackberry stained more than red oak sweetgum, or cottonwood. After a year in storage under continuous sprinkling hackberry lost 14.3 percent of its original value as compared to a 0.3 to 1. percent loss for other species. Dry-stored logs were valueless after 1 year.

End-coating of logs with bituminous compounds or end-spraying with solu tions of sodium pentachlorophenate are not particularly effective in the South a inhibitors of stain and fungus attack on hardwoods (Burkhardt and Wagne 1978; DeGroot and Eslyn 1978).[6]

A sour odor from bacterial attack may develop in logs stored for extende periods—e.g., 6 months—under water, even if the water contains 0.5 percer sodium pentachlorophenate; Highley and Lutz (1970) found that yellow-popla logs infected with bacteria were more permeable to water than normal log because of degradation of pit membranes, and had increased pH (7.5 compare to 4.5 for normal wood).[6]

Results with pine pulpwood bolts (McKee and Daniel 1966) indicate tha freshly cut hardwood bolts might be safely stored for 2 years by encapsulatin them with 20-mil-thick, black polyethylene film. Yard sanitation reduces th rate and amount of early infection but does not totally prevent decay or preclud blue stain. Other methods used to protect logs and pulpwood in the United State and Canada have been reviewed in detail by Scheffer (1969).

PULPWOOD CHIPS[6]

Chipping of wood favors mold in chip piles by greatly increasing the surfac area per-unit of wood (Bergman and Nilsson 1971). Soft-rot organisms are th predominant deteriorators of piled southern hardwood chips (Lindgren and Es lyn 1961; Eslyn 1967; Eslyn and Davidson (1976).

Symptoms of microbial deterioration in hardwood chips are mold or light stain, dark stain, and typical decay. Chips with mold and light-stain infection show fungus discolorations on surfaces but only occasionally in the interior wood. Chips with dark stain are almost black and usually are discolored throughout; dark stain occurs most often in the pile shell. In black tupelo, chip decay causes a bleaching and eventual softening of the wood. Decay begins during the first month of storage; by 6 months, specific gravity of chips in the pile shell decreases 20 to 30 percent. Bleaching develops more slowly in decaying oak chips than in black tupelo (Lindgren and Eslyn 1961; Eslyn 1967).

Compaction apparently reduces specific gravity loss in chip piles. Specific gravity losses in compacted portions of oak and gum (sweetgum and *Nyssa* sp.) piles stored from May to October were 3.8 and 6.2 percent; losses in similar uncompacted piles were about 17 and 26 percent. In compacted piles, losses in oak chips were no greater than those expected in bolts stored under similar environmental conditions, but losses in gum chips exceeded those in bolts (Bois et al. 1962).

With hardwood chips, as with stored bolts, wood decay causes a reduction in pulp tearing strength but little or no loss of tensile strength. Tearing strength of pulp from oak and gum chips was reduced 2 to 3 percent per month of storage in compacted piles (Bois et al. 1962). A 17-percent reduction in pulp tearing strength occurred with 7 months' storage of hardwood chips at Panama City, Florida (Rhyne and Brinkley 1961).

Another problem in chip storage is heat buildup caused by microorganisms and chemical reactions. Temperatures within chip piles may increase appreciably within a few weeks after construction. In aspen (*Populus tremuloides* Michx.), mesophyllic microbial growth and respiration of living cells in wood chips contribute to the temperature rise during the first 7 to 10 days of storage to a high of about 45°C. Direct chemical oxidations become important above 42°C, and thermophyllic microorganisms begin to grow when temperatures surpass 45°C (Feist et al. 1973ab). Most wood-decaying Basidiomycetes that inhabit chip piles would be killed when temperatures in the piles reach 50°C. *Phanerochaete chrysosporium* Burds., which causes a white rot in chips and is usually temperature-tolerant, would be lost at 60°C. Many fungi imperfecti, some of which cause serious soft rot, survive at temperatures over 50°C, but only two fungi, ascomycetes which may cause a slight soft rot, can survive temperatures above 70°C. Combinations of low pH, high humidity, and high temperatures suppress fungal growth. Consequently, the top central regions of hot chip piles, where acetic acid has accumulated, are often sterile (Hulme and Stranks 1976). Some thermophyllic bacteria grow in temperatures of up to 75°C (Bergman 1973). Temperatures of 100°C have been measured in a pile of unscreened chips consisting of 90 percent birch (*Betula pubescens* and *B. verrucosa*) chips. Chips removed from such a zone burst into flames within a few minutes (Bergman 1974).

The inclusion of fines (small particulates) within a chip pile increases the risk of spontaneous ignition because they may have a high resin content (see analysis of spruce sawdust by Back and Carlson 1955) and block heat transfer. Resins lower the temperatures required for spontaneous ignition (Heinrich and Kaesche-Krischer 1962; Kinbara and Kawasaki 1967). Intensified heat build-up in pockets of fines, sawdust, or bark may have contributed to a burrowing fire in a pile of unscreened maple and beech chips (from logs that were not debarked before chipping) in New Brunswick (Cole 1972).

Combustion is not the only adverse effect of heat in chip piles. Kraft pulp yields of quaking aspen decreased 21 to 25 percent after 3 months' storage at 65.5°C and 30 to 31 percent after 6 months' storage. High concentrations of water-soluble acids hydrolyzed wood carbohydrates, resulting in increased hot water- and alcohol-benzene-soluble extractives. Pulp from this wood had strengths 10 to 35 percent below controls (Feist et al. 1973a).

Several approaches have been tried to prevent microbial degradation and heat buildup in chip piles. Surface sterilization of chips before storage has met with mixed results. Sapwood chips of sugar maple (*Acer saccharum* Marsh.) exposed to near-ultraviolet light (250 nm) for 24 hours developed more fungal discolorations and more soft rot damage than did control chips (Desai and Shields 1971). In another study, a 5 to 9 percent increase in ovendry yields after storage was obtained from radiated Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) chips stored for 8 months (Nicholls et al. 1974).

Treating chip piles with chlorophenates, mercurials, and nickel compounds may not be desirable because of cost and of possible environmental hazard (Smith and Hatton 1971).[6] Several organic sulfur compounds, heterocyclic nitrogen compounds, aromatic compounds (Eslyn 1973a), and propionic acid (Eslyn 1973b) protected red pine (*Pinus resinosa* Ait.) chips in laboratory tests. Neither nickel sulfate, the sodium salt of 2-mercaptobenzothiazole, a mixture of sodium salts or chlorinated phenols, nor a synthetic kraft green liquor retarded loss of brightness in simulated piles of aspen chips, but synthetic kraft green liquor prevented loss of wood substance (Springer et al. 1969, 1971, 1973).[6] Under laboratory conditions, treatment of aspen wood chips with an aqueous solution of 0.20 percent potassium N-methyl, N-hydroxymethyldithiocarbamate, and 0.05 percent sodium 2-mercaptobenzothiazole, prevented chip heating, loss in brightness, and growth of fungi and bacteria.[6] The estimated cost of this treatment in 1973 was about $4.50/ton of ovendry wood (Springer et al. 1973).

Freshly cut aspen chips were protected for 6 months by sealing them within an air-tight covering of polyethylene film (Feist et al. 1971). The weight loss in the aspen chips was 2.3 percent, and there was some loss in chip brightness; kraft pulping of stored chips gave essentially the same overall pulp yield as fresh chips, and pulp properties were not significantly affected by storage. Eslyn and Laundrie (1975) also excluded oxygen from stored aspen chips, by placing them under water or in an atmosphere of 95 percent nitrogen and 5 percent carbon dioxide; they found no significant losses in wood specific gravity or in yield and quality of pulps made from the chips.

Spontaneous ignition has not occurred in piles stored less than 6 months. For longer storage periods, Bergman (1974) suggests metering pile temperatures with thermocouples placed in the pile during construction and reclaiming piles as soon as they reach 75°C. Screening chips before storage, keeping piles small, and preventing contamination of the pile with metallic objects are other suggested precautions against spontaneous ignition (Cole 1972; Bergman 1974).

Springer et al. (1978) found that treating screened southern pine chips by immersion in a dilute aqueous solution of formaldehyde and P-nitrophenol effectively preserved the chips during 6 months' storage in simulators of exterior piles.[6] They concluded that the treatment may be cost-effective for pulpwood chips, but that it is probably not for chips stored for fuel.

More information on chip storage is included in a recent bibliography of all literature pertaining to the biological, chemical, and physical factors that cause changes in pulpwood quality (Weiner et al. 1974), and in the TAPPI monograph on chip quality (Hatton 1979, chapters 11 and 12).

HOGGED FUEL

The progress of weight loss in piles of chipped fuel wood (**hogged fuel**) is similar to that in piles of pulpwood chips, except that in piles of hogged fuel incorporating leaves and bark, deterioration is more rapid and problems with heat buildup more severe. In a laboratory-scale storage study, Zoch et al. (1976) found aspen whole-tree chips lost ovendry weight six times faster than clean debarked chips. Moran[7] reported that the decay rate for mixed hardwood whole-tree chips (mainly oak) stored in an outside pile was approximately three times that for clean debarked chips. Weight loss, and changes in temperature, moisture content, heat of combusion, and pH are all manifestations of incompletely understood reactions within fuel piles. White and DeLuca (1978) have provided data on these changes, which significantly affect the utility of hardwood sawdust and bark for fuel. In their study, three fuel piles were analyzed over a period of 6 months from the time of pile establishment. The three fuel piles differed, as follows (all piles were completed by July 30, 1976):

- Hardwood bark (predominantly oak and yellow-poplar) produced by a rosser-head debarker was piled in Callaghan, Virginia with a front end loader into a round-top pile 10 feet high, 30 feet wide, and 70 feet long.
- Mixed hardwood (predominantly oak and yellow-poplar) and southern pine sawdust was pneumatically piled in Martinsville, Virginia into a 25-foot-high cone-shaped pile with 45-degree side slope.
- Southern pine bark produced on a mechanical ring debarker, and subsequently hogged, was belt-conveyed into a 25-foot-high cone-shaped pile with 45-degree side slope. This pile was also located in Martinsville, Virginia.

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[7] Moran, J. S. 1975. Kraft mill experience with whole-tree chips. Presentation at TAPPI Annual Meeting, New York, Feb.

Temperature changes.—Because several serious fires have occurred in piles of whole-tree chips (Boggan 1977; Southern Pulp and Paper Manufacturers 1977), knowledge of temperature build-up within fuel piles is needed. White and Deluca (1978) monitored internal temperatures as a function of storage time (fig. 11-21); temperature rose rapidly and remained relatively constant for the 6 months of storage. Hottest zones were near the center of the base of each pile; zones near pile perimeters were 10 to 20°F cooler. Pine bark reached and maintained a temperature of about 170° to 190°F within 3 weeks after pile construction. Mixed hardwood bark was about 25°F below this. The internal temperature of the mixed hardwood-softwood sawdust was the lowest, stabilizing at about 108° to 130°F within 10 days.

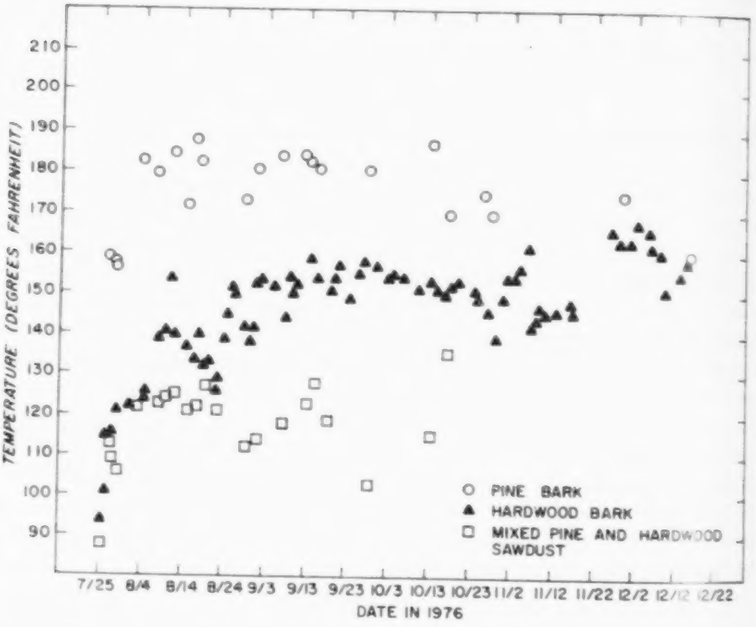

Figure 11-21.—Internal temperatures measured in Virginia in outside storage piles of hardwood bark, southern pine bark, and mixed hardwood-pine sawdust, related to storage time. The hardwoods were predominantly oaks and yellow-poplar. (Drawing after White and DeLuca 1978.)

Moisture content changes.—White and DeLuca (1978) found that hardwood bark gained moisture content—the pile-average changing from 60 percent to over 100 percent, dry basis, while mixed hardwood-pine sawdust declined in moisture content from 80 percent to below 70 percent. Moisture content of the southern pine bark declined sharply from 80 percent to about 30 percent. Pile surfaces were wettest (160 percent to 190 percent), while interiors had lowest moisture content (fig. 11-22). Internal moisture contents of all three piles were unaffected by changes in ambient external temperature; only the hardwood bark pile indicated sensitivity to daily precipitation.

Heat of combustion changes.—Springer et al. (1978) observed no diminution in the heating value (as measured by a bomb calorimeter) of ovendry whole-tree chips of southern pine after 6 months of simulated exterior storage. White and DeLuca (1978) found that heats of combustion increased 5 percent to 7 percent during 6 months of storage (fig. 11-23), as follows:

Fuel	Heat of combustion	
	Initial	After 6 months
	-----Btu per ovendry pound-----	
Hardwood bark	7,978	8,322
Hardwood-pine sawdust	8,475	8,920
Pine bark	8,896	9,611

Although the energy per unit weight of dry fuel was found to be higher in the residues stored for 6 months, total energy in the piles was less because of loss of mass as heat during storage.

White et al. (1983)* found that particulate fuels stored outside in Virginia undergo complex changes in heat of combustion and moisture content. They concluded that higher heating values of hardwood whole-tree chips and hardwood bark declined by about 9 and 7 percent and sawdust by about 3 percent during one year's storage in 15-foot cone-shaped piles; the observed decrease occurred only after about 4 months of storage. Increases in the moisture content of such particulate fuels, and subsequent decrease in higher heating value, resulted in a significant decrease in the average net heating value of stored fuels. Most of the loss in average net heating value occurred during the first 2 to 4 months of storage, due principally to increases in fuel moisture content at the pile surface.

pH changes.—When burned, alkaline or acidic fuels can corrode combustion chambers, boiler tubes, and ductwork; changes in pH of woody fuels during storage are therefore of interest. White and DeLuca (1978) found that the pH of hardwood bark, pine bark, and hardwood-pine sawdust declined significantly during 6 months of storage. Initial pH was in the range from 5 to 7, while ending pH was about 4 (fig. 11-24).

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*White, M.S., M.L. Curtis, R.L. Sarles, and D.W. Green. 1983. Effects of outside storage on the energy potential of hardwood particulate fuels: Part II. Higher and net heating values. Forest Products Journal. 33 (11/12):61-65.

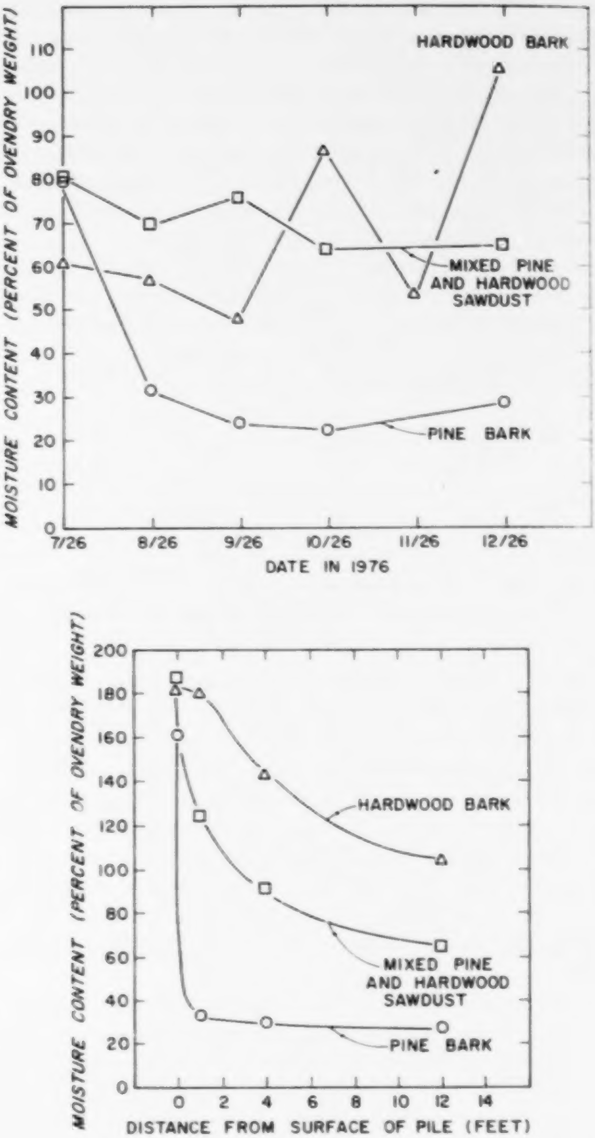

Figure 11-22.—Moisture content in hardwood bark, southern pine bark, and mixed hardwood-pine sawdust piled outside in Virginia. (Top) Average moisture content of pile related to storage time. (Bottom) Moisture content of residues within the experimental piles after 5 months storage related to distance from the pile surface. (Drawing after White and DeLuca 1978.)

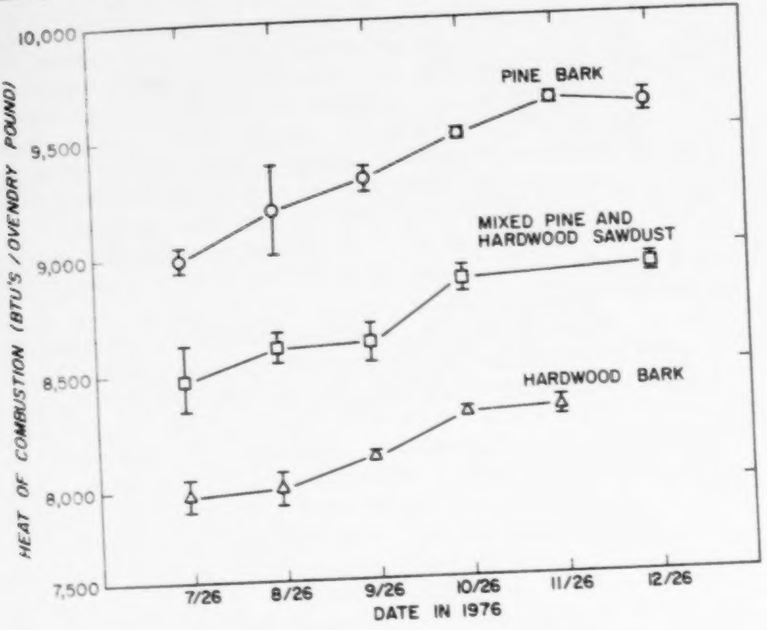

Figure 11-23.—**Average heat of combustion of hardwood bark, southern pine bark, and mixed hardwood-pine sawdust related to storage time in experimental outside storage piles in Virginia. Vertical bars show standard deviation of five replicates. (Drawing after White and DeLuca 1978.)**

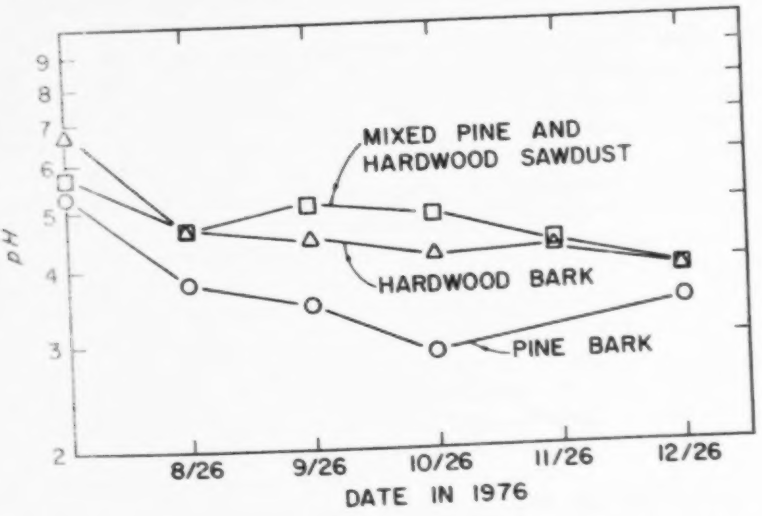

Figure 11-24.—**Average pH of hardwood bark, southern pine bark, and mixed hardwood-pine sawdust related to storage time in experimental outside piles in Virginia. (Drawing after White and DeLuca 1978.)**

LUMBER[6]

Stain fungi pose a hazard to green lumber. These fungi require temperatures between 3°C and 35°C and a minimum wood moisture content of about 24 percent (Lindgren 1942). In lumber, they usually grow through the wood by cell-to-cell penetration via pit pairs. Direct penetration of cell walls seldom occurs. Thus, stain fungi contribute mainly to wood discoloration and increased permeability (Campbell 1959) and have only a minor effect on strength. Mycelium of stain and decay fungi will survive several months in air-dried wood. Dried wood must therefore remain dry to insure continued protection (Scheffer and Chidester 1948).

Blue stain of lumber is controlled by surface treatment of unseasoned lumber with protective chemicals (Verrall 1945) or by rapid drying, especially kiln-drying.[6] Chlorinated phenols, some in mixtures with borax, have been used extensively for chemical protection (Roff et al. 1974).[6] Borax solutions alone will control stain on sweetgum and other southern hardwoods but not on southern pine (Scheffer and Lindgren 1940).[6] Chemicals with an alkaline reaction tend to turn sweetgum sapwoods reddish brown (Cockcroft and Levy 1973). N-(1,1,2,2-tetrachloroethylthio)-3a,4,7,7a-tetrahydropthalimide is superior to sodium pentachlorophenate in controlling sap stain and decay of *Pinus radiata* timber in New Zealand and costs about the same (Butcher 1973); it may hold promise for hardwoods.[6] Two related agricultural fungicides, Captan and Folpet (N-trichloromethylthio)-4-cyclohexene-1, 2-dicarboximide 50 percent and N-(trichloromethylthio) phthalimide 75 percent, respectively) also hold promise as antistain compounds (Unligil 1976).[6]

Cassens and Eslyn (1981) found that in laboratory tests Bardac 22 (didecyl dimethylammonium chloride) and Troysan (3-iodo-2-propynyl butyl carbamate) in polyphase anti-mildew emulsion and in water dispersible preparations were effective in controlling sapstain and mold fungi in yellow-poplar sapwood.[6]

Lumber, once dried, can be effectively protected from stain and decay with any covering that adequately shields it from rewetting. Encapsulation of dried lumber in either heavy plastic or paper, however apparently will not provide the necessary protection from moisture (Applefield 1964). Inclusion of a volatile fungistat or insecticide within well-sealed packages might help. Moth crystals (saturated vapors of paradichlorobenzene) provide short term, superficial suppression of fungi and insects on wood (Scheffer and Graham 1972). The fumigant sodium N-methyl-dithiocarbamate effectively eradicated fungi from wood chips until it volatilized and escaped from the laboratory test chamber (Eslyn 1973a).[6] Experiences gained with the use of volatile chemicals in reducing post-harvest deterioration of fruits and vegetables (Eckert and Sommer 1967; Cappellini et al. 1968; Cappellini and Peterson 1969; Coursey and Booth 1972) may provide further insights for protecting wood products in storage and transit.

Difficulties in drying oak boards may be related to bacterial stem infections in the living tree. In northern red oak, for example, anaerobic bacteria apparently gain entry through insect wounds in roots, root collar, and butt. Lumber heartwood from infected trees, especially from butt logs, is more susceptible to honeycomb and ring failure during kiln-drying than is similar lumber from noninfected heartwood. Before drying, infected heartwood appears sound and clear of stains, but it can be identified by the sour vinegar and rancid odors of volatile fatty acids produced by anaerobic bacteria (Ward et al. 1972). Separation of green lumber with rancid heartwood from normal green lumber should permit accelerated kiln-drying of the normal oak lumber without causing honeycomb. Lumber with rancid heartwood should be dried with a mild kiln schedule.

COMPOSITE PRODUCTS[6]

The microbiology of fungal attack on composite wood products is pertinent because such products will probably play a major role in utilization of pine-site hardwoods. Literature specific to these hardwoods is scarce, but some data are published on plywood, particleboard, fiberboard, insulation board, and asphalt roofing shingles.

The decay resistance of sweetgum **plywood** varies with adhesive used in bonding; none give complete protection, but a liquid phenolic resin with a pH of 2.0 gave the best protection of any of the adhesives studied (Englerth 1950).

Toole and Barnes (1974) reviewed microbiological aspects of **particleboard** deterioration. They found particleboard significantly less susceptible to biodeterioration than solid wood; this agrees with findings of Behr (1972) and Stolley (1958). Schmidt et al. (1978) found that losses of internal bond and bending strengths in the major types of commercial particleboard are considerably greater when they are subjected to fungi than when submerged in water, even though weight loss in boards exposed to fungi may be small. This was true especially of boards bonded with urea formaldehyde, but could also apply to newly manufactured phenol-formaldehyde boards subjected to leaching.

Typical wood decay fungi that cause rot in trees do not attack wood **fiberboards** used in buildings (Merrill 1965; Merrill and Hossfeld 1965). The inside of insulating board, for example, is sterile when it leaves the drying oven (Schipper and French 1971), but if it is wetted during service, it can be colonized by cellulolytic Ascomycetes, such as *Chaetomium globosum* Kunze ex Fr. and by molds, such as *Aspergillus* and *Penicillium*.

Fiberboards can be protected with a biocide such as sodium pentachlorophenate added to the furnish (Englerth 1946) before board composition. The minimum amount needed has been variously estimated.[6] The greatest decay reduction per unit of preservative occurs when products are treated with about 0.4 percent pentachlorophenol or its copper salt copper pentachlorophenate (Merrill and French 1963).[6] These retentions completely inhibited decay in tests where the assay fungus, *Lenzites trabea* (Pers. ex Fr.) Fr. (*Gloeophyllum trabeum* (Pers. ex Fr.) Murr.), derived all nutrients from the fiberboard test unit.

To prevent brown spotting in coatings on **insulation board**, French and Christensen (1969) found that concentrations above 0.5 percent of pentachlorophenol were required.[6]

Asphalt **roofing shingles**, which are composed mainly of wood fibers, generally give 7 to 20 years' service before they must be replaced because of discoloration or deterioration. *Gloeocapsa magna* (Brēb) Kutz, a blue-green alga, was consistently responsible for the discoloration of roofing shingles from 10 houses along the Mississippi Gulf Coast (Amburgey 1974). Such discoloration of shingles can be prevented, or discolored ones gradually cleaned, by spraying them annually with 0.52 percent sodium hypochlorite (10 percent Chlorox). Discolored roofs can be cleaned immediately and will remain clean for at least 5 years if sprayed with 3.94 percent sodium hypochlorite (75 percent Chlorox). Applying aluminum or galvanized steel flashing near the roof peak will inhibit discoloration of new shingles, but will not clean discolored ones (Amburgey 1978).

WOOD IN USE

Fungus damage to wood in use is mainly decay. Some, perhaps most, hardwoods in use have been seasoned, though not always adequately. While stain or mold fungi occur on such wood when rewetted, they grow there less prolifically than on green wood. All decayers of southern hardwoods require free water in the wood (i.e., moisture content above fiber saturation). Studies of fungus deterioration of hardwoods in use therefore aim at keeping wood dry, or the use of preservatives where wood cannot be kept dry.

Important uses of kiln dry hardwoods include residential and industrial flooring, interior wall panelling, sports gear, and interior millwork. In these applications wood is normally kept dry and decay is not a problem. One of the most interesting applications of untreated southern hardwood is that of white oak heartwood in frames of minesweepers. Inspection of such minesweepers after 15 years of service disclosed no fungus rot of significance (Highley et al. 1971).

Hardwoods from pine sites are frequently used on contact with the soil or fully exposed to the weather. In such applications, e.g., as crossties, posts, or mineprops, their service life when untreated is generally short, but varies considerably with species. In southern locations, untreated fence posts of pine site hardwoods can be expected to serve fewer than 6 years (table 11-4).

Untreated oak crossties have an average service life of about 5 to 17 years depending on species and location as follows (Blew 1966):

Installation and oak species	Average service life
	Years
Chicago, Burlington, and Quincy Railroad, test track established in 1909—one east, and one west of the Mississippi River	
Northern red	5.3
Pin (*Quercus palustris* Muenchh.)	6.3
White	11.1
Chicago, Milwaukee, St. Paul, and Pacific Railway test track in Wisconsin	
Blackjack	17.0
Northern red	8.7
White	12.4

Treatments to lengthen service life are described in chapter 21.

TABLE 11-4.—*Service records of untreated hardwood fenceposts* (Data from Gjovik and Davidson 1975)[1]

Species	Form	Location of test	Service life[2]
			Years
Ash, green	Round	Halsey, Nebr.	18.7
Ash, green	Round	Miles City, Mont.	8.6
Ash, white	Round	Madison, Wis.	4.3
Elm, slippery[3]	Round	Oregon, Wis.	3.8
Hickory, mockernut	Round	Saucier, Miss.	3.5
Hickory, shagbark	Round	Oregon, Wis.	4.0
Hickory, sp.	Round	Norris, Tenn.	4.7
Hickory, sp.	Round	Saucier, Miss.	2.8
Maple, red	Round	College Park, Md.	3.8
Oak, black	Round	Norris, Tenn.	2.8
Oak, blackjack	Square	Madison, Wis.	8.4
Oak, blackjack	Round	Ava, Mo.	6.0
Oak, blackjack	Square	Madison, Wis.	7.9
Oak, northern red	Round	Athens, Ga.	4.3
Oak, southern red	Round	Saucier, Miss.	2.8
Oak, overcup[4]	Round	Stoneville, Miss.	4.3
Oak, overcup	Split	Stoneville, Miss.	5.0
Osage orange[5]	Round and split	Childress, Tex.	43.0
Sweetbay	Round	Saucier, Miss.	1.6
Sweetgum	Round	Athens, Ga.	2.2
Sweetgum	Round	College Park, Md.	4.2
Sweetgum	Round	Wilson Dam, Ala.	2.3
Sweetgum	Round	Saucier, Miss.	1.8
Tupelo, black	Round	Norris, Tenn.	3.4
Tupelo, black	Round	College Park, Md.	4.2
Tupelo, water[6]	Round	Saucier, Miss.	2.1

[1] Round posts were 3 to 7 inches in diameter; square posts measured 4 by 4 inches.

[2] Posts that would break off with a moderate push or that would no longer support a fence were considered failures.

[3] *Ulmus rubra* Muhl.

[4] *Quercus lyrata* Walt.

[5] *Maclura* Nutt.

[6] *Nyssa aquatica* L.

11-7 INSECTS THAT ATTACK TREES

Like diseases, insects that attack living trees slow growth and lower the value of wood produced. Trunk borers most significantly lower wood value and may introduce decay; defoliators, seed destroyers, and twig, bark, and root insects cause growth loss and adversely affect tree form. Donley and Worley (1976) have related stand age to loss in value of oak trees attacked by these types of insects. Such losses in all pine-site hardwoods total millions of dollars annually (Morris 1959, 1964; Solomon 1977a).

Among the thousands of insects that attack southern hardwoods, a few of major importance are described in the following paragraphs. For a more complete listing of forest insects, the reader should refer to Baker (1972). Insects that attack oak are illustrated in color by Solomon et al. (1980).

FOLIAGE INSECTS

Defoliators probably cause more growth reduction and mortality among pine-site hardwoods than any other group of insects. The degree of injury depends on the extent of defoliation because leaves synthesize the food needed by the tree for sustenance. Severe defoliation reduces the production of wood, especially when it occurs early in the growing season. Successive annual defoliations kill branches and entire trees (Rexrode 1971). The forest tent caterpillar (*Malacosoma disstria* Hbn.) is a principal hardwood defoliator in the South. Kowal and Ebel (1971) have provided brief descriptions of the insect and eight other major defoliators of pine-site hardwoods; the descriptions follow in alphabetical order by species name. Defoliators of lessser importance, and not described, are the oak sawfly (Anonymous 1976), the yellow-poplar weevil (Burns 1971a), and the hackberry butterfly (Solomon et al. 1975).

***Alsophila pometaria* (Harris).**—The **fall cankerworm** defoliates oaks, red maple, hickories, ashes, and other hardwoods. Moths emerge and lay eggs on twigs in late fall and early winter. Caterpillars feed from early May to mid-June, then drop to the ground to pupate in the soil. The male moth is brownish gray; the female is wingless, shiny, and ash-gray in color. Abdomens of the moths are without spines. The caterpillar is one-inch long, and green, with a dark stripe down the middle of the back.

***Anisota senatoria* (J.E. Smith).—Orange-striped oakworms** feed in clusters to defoliate oak species. Moths emerge from July to August. Coral red eggs are laid in clusters on under sides of leaves. Caterpillars are found from July to August. They hibernate and pupate in the soil.

***Baliosus ruber* (Web.)**—The **basswood leafminer** skeletonizes and mines leaves of oaks and other hardwoods giving crowns a scorched appearance. Beetles are active in the spring and deposit eggs on the leaves. New adults skeletonize the leaves in July; a small second brood appears in September. Insects overwinter in the adult stage. The beetles are nearly 1/4-inch long, wedge-shaped, and reddish to dark brown in color.

***Ennomos subsignarius* (Hbn.).**—The **elm spanworm** defoliates hickories, oaks, and red maple. Caterpillars are abundant in May when new foliage develops. They pupate in silky cocoons on the foliage and in bark crevices. Moths emerge in late June to early July and lay eggs in masses, largely on twigs. Caterpillars, commonly called inch-worms or measuring worms, are green to brown and about 2 inches long when full grown. Moths are almost pure white with wingspread of 1¼ inches.

***Heterocampa manteo* (Dbldy.)**—The **variable oak leaf caterpillar** defoliates oaks, elms, and other hardwoods. Moths emerge during June and July, caterpillars occur from July to October. Winter is passed as prepupal larvae in leaf-mold or topsoil. The moth has indistinct markings, is ashy-gray, and has a wingspan of 1½ inches. The caterpillar is 1½ inches long, with variable coloration. The head is large, with two broad lateral bands, the inner one brownish black, the outer one creamy white. The body is smooth and yellow-green.

***Hyphantria cunea* (Drury).**—The **fall webworm** defoliates numerous southern hardwoods; it is common on hickory, pecan, and persimmon. The caterpillars, in webs, are noticeable in late July and in August. These webs cover large areas of foliage, within which they feed. In August, the insects enter the topsoil, where they hibernate as pupae. Moths emerge in late June or early July. Eggs are laid in masses of four to five hundred, usually on the undersides of leaves. There are as many as four generations annually in the deep South (Filer et al. 1977). The caterpillars are 1¼ inches long and are greenish-yellow with a dark stripe down their backs and yellow stripes on their sides; they have many light-colored hairs. The moths are white with a wingspread of 1¼ inches.

***Malacosoma americanum* (F.)**—The **eastern tent caterpillar** defoliates numerous southern hardwoods, including apple and cherry trees. The insect has habits and life history similar to the forest tent caterpillar except that it forms large tents in forks of limbs to shelter larvae. Larvae leave the tents to feed. Caterpillars are 1½ inches long, reddish brown, long-haired, and have a white line down their backs, with blue and brown spots along their sides. Adult moths are buff colored with two oblique white lines on upper wings; wingspread is 1¼ inches.

***Malacosoma disstria* (Hbn.).**—The **forest tent caterpillar** defoliates black tupelo and oaks. The caterpillars, most abundant in late May and early June, pupate in late June. Cocoons are attached to undergrowth, bark, and rocks; no definite tent is formed as a larval shelter. Moths emerge in July and lay eggs in bands around twigs. Hibernation occurs in the egg stage. The caterpillars are about 1½ inches long, dull brown, long-haired, and have diamond spots along their backs and blue spots along their sides. Adult moths are buff colored with two oblique dark lines on their upper wings, and have a wingspan of 1¼ inches.

***Paleacrita vernata* (Peck).—Spring cankerworm** defoliates elms, hickories, oaks, red maple, and other hardwoods—leaving only mid-ribs and veins of leaves. Moths emerge and lay eggs in March and April in bark crevices. Caterpillars feed from early May to mid-June, then drop to the ground and pupate in the soil. The caterpillar is 1 inch long, reddish, yellow-brown, yellow-green, to blackish. The male spring cankerworm moth resembles the fall cankerworm moth except for two rows of reddish spines on the abdomen; these spines are very noticeable on the female.

SEED DESTROYERS

Seeds of pine-site hardwoods are extensively attacked by numerous insects. Hickory nuts and acorns have been particularly studied, in the interest of regenerating hickories and oaks and as major foods for animals and birds.

Acorns.—Acorns are heavily damaged by several species of weevils, moths, and wasps; fungi are also responsible for small losses. Downs and McQuilkin (1944) found that about a third of well-developed acorns from five oak species sampled from two Appalachian forests in North Carolina and Georgia were damaged by insects as follows:

Oak species	Damaged by insects
	Percent of well-developed acorns
Black	37
Chestnut	34
White	32
Scarlet	31
Northern red	24

In the Missouri Ozarks, Burns et al. (1954) found that less than half the acorns they collected were sound. In west-central Louisiana and East Texas, Reid and Goodrum (1957) observed less damage, as follows:

Oak species	Unsound acorns (all causes)
	Percent
Water	28
Blackjack	25
Post	23
Southern red	19
White	10

Gibson (1972) reported that insect damage to white oak acorns is extensive (10 to 100 percent) throughout the range of the species; he found that seven *Curculio* weevil species, three *Conotrachelus* weevil species, one moth (*Melissopus latiferreanus* Wlsm.), and two gall wasps (*Cynips glandulosus* Beutm. and *Callirhytis* sp.) cause most of the damage.

Hickory nuts.—There are few data on insect attack on hickory seeds, or the extent of damage, but Donley (1971) in describing the **hickory nut weevil** (*Curculio caryae* (Horn)) noted that destroyed seed ranges from 5 to 90 percent. Adult weevils of this species emerge from the soil as early as July (in Ohio) and can be found on hickories almost as soon as the nuts start to form. The female lays her eggs within the nut while husks are tight and still green. The larvae live in the nuts for almost 2 months and when mature make small circular holes in the nut shells from which they exit to the soil. Some larvae pupate the first spring, others the second.

TWIG, BRANCH, AND TERMINAL INSECTS

Of the many insects that attack branches of pine-site hardwoods, five that cause significant damage are described in the following paragraphs. Each of the five damages trees by a different mode of action.

***Agrilus bilineatus* (Web.).**—Larvae of the **two-lined chestnut borer** kill limbs of oaks and other hardwoods by boring zigzag galleries below the bark until limbs are girdled. Crowns of trees die gradually as attack progresses toward the trunk. In spring the beetles, which are about 1/2-inch long and bluish black with stripes along wing covers, lay eggs in the branch bark of weak trees. The larvae hibernate in the bark. Life cycle in the South is 1 year (Kowal and Ebel 1971).

Andricus sp.—**Cynipid gall wasps,** probably endemic throughout the South, cause large galls, girdle twigs, and kill leaves and buds. Southern red oak and water oak are the pine-site hardwoods most frequently attacked (Morris 1955). Females deposit their eggs in the tissues of all parts of the host tree from roots to the flowers. Gall production is believed to result from reaction of meristematic tissues to stimuli produced by the larvae (Baker 1972).

***Goes debilis* (Leconte).**—The **oak branch borer** attacks southern oaks of several species (Baker 1972). Solomon (1977b) found that in central Mississippi it has a life cycle of either 3 or 4 years. Adult beetles, 10 to 16 mm long,emerge during May and early June and females oviposit preferably on lateral branches, and on stems 9 to 38 mm in diamter, usually near crooks, branch crotches, and other stem irregularities. The larvae construct galleries 30 to 70 mm long and 4 to 6 mm in diameter. After a year or so of larval tunneling, infested stems become swollen and gall-like, and often break or die back. Woodpeckers are the most important natural enemy, capturing about two-thirds of the larvae (Solomon 1977b).

***Magicicada septendecim* (L.).**—The **periodical cicada** is widely distributed in the southern pine region where it lays its eggs in many hardwoods including oaks, hickories, elms, ashes, sweetgum, and yellow-poplar. Adults are nearly 2 inches long. They insert eggs in slits (closely spaced punctures) made in tender branch terminals, often killing 6 or 8 inches of the tip. The nymphs fall to the ground where they feed on suitable roots—usually 18 to 24 inches below the surface. They emerge from the ground 13 to 17 years later, usually at night in late April in the South, to molt to the adult stage and mate, but cause no feeding damage. Soon after, the males begin drumming, causing a loud and incessant noise during daylight hours; volume increases as temperature rises. Closely related, but slightly larger, are the **dog-day cicadas**, often called harvest flies (Baker 1972).

***Toumeyella liriodendri* (Gemlin).**—The **tulip tree scale** is a sucking insect that damages yellow-poplar seedlings and saplings by removing phloem sap from stems and twigs less than 1.2 cm in diameter, and from callus wound tissue. Damage of significance is stem crook, as lateral branches assume apical dominance after the leader is killed. The scale insect completes one generation per year. From mid-August until frost the females give birth to tiny crawlers, the motile stage of the insect. The crawlers insert mouthparts into the tree and are fixed there, molting within a few weeks to the second instar or overwintering stage. The size of a pinhead, and charcoal colored, they are found on the undersides of twigs and in other protected locations. In spring the scales begin to grow and excrete honeydew. In late May the males pupate under an opaque whitish cover, which remains visible after the males emerge and mate with the females in mid-June. The females grow until August, when they mature and produce crawlers (Burns 1970).

BARK BEETLES

The three bark beetles that are probably most damaging to pine-site hardwoods cause their damage by different modes of attack; one is a vector for elm disease, another causes bark inclusions in stems of oaks, and the third kills hickories by girdling them.

Dutch elm disease.—Dutch elm disease, caused by *Ceratocystis ulmi* (Buism.) C. Moreau, was first confirmed in the United States in 1930 from symptomatic trees in Cleveland, Ohio. By 1964 the disease was reported as far south as North Carolina, Tennessee, Arkansas, and Oklahoma. Since then it has spread south to Georgia, Mississippi, Alabama, Texas, and South Carolina. The **smaller European elm bark beetle,** *Scolytus multistriatus* (Marsham), the primary vector of *C. ulmi*, was first collected and identified in the United States in 1909 at Cambridge, Mass., and by 1970 had been reported in all of the contiguous 48 States except Arizona, Florida, and Montana. Although its direct damage to elms is nominal, its wide distribution threatens to spread Dutch elm disease throughout all elm-growing regions of this country (Barger and Hock 1971). Elm mortality from the disease is highest in northeastern United States; it is lowest in areas bordering the Gulf of Mexico, and intermediate at the latitudes of northern Alabama. Peacock (1975) has summarized research on chemical and biological controls for elm bark beetles.

***Nitidulid* sp.** —**Nitidulid beetles** are attracted to tree wounds, borer holes (e.g., from the round-headed borer, *Romaleum* sp.), and other bark openings from which sap flows. The adults feed on sap and deposit eggs. The larvae feed on inner bark as well as sap, killing patches of cambium before dropping to the ground to pupate. The injured area dries up and heals, to become a pocket of ingrown bark and stained wood that remains as a defect in lumber and veneer (Morris 1965). The beetles occur throughout the South on poorer sites. Pine site oaks attacked include laurel, water, cherrybark, black, and white oaks; also attacked are black tupelo, hickories, and yellow-poplar. Damage is significant; for example, veneer from black tupelo trees that have been attacked is reduced to core-stock grade (Morris 1955). Solomon (1976) concluded that the nitidulid sap beetles are not primary agents in the origin of sap spots leading to ingrown bark, but their feeding possibly enlarges them; wood borers are chiefly responsible for origin of sap spots.

***Scolytus quadrispinosus* Say.**—The **hickory bark beetle** kills hickories and pecans; trees die from girdling by larvae and beetles which tunnel beneath the bark. The galleries of adults are etched into the inner bark; brood tunnels, which branch off like the legs of a centipede, may be etched into the wood where bark is thin. The insect is occasionally epidemic. Beetles, brown to black and about 3/16-inch long, fly in the early spring and later summer. The brood hibernates as full-grown larvae in the bark. Abnormal drop and wilt of foliage is an early sign of attack. Trees may die suddenly or gradually (Kowal and Ebel 1971).

TRUNK BORERS

Of all the insects that attack pine-site hardwoods, trunk borers do the most economic damage. Their larvae construct galleries in the wood of living trees, damaging merchantable stem portions. Quality is greatly reduced by bore holes and associated defects, especially in the most valuable butt logs. Secondary damage results from introduction of wood-rot fungi, access by carpenter ants, and attraction of woodpeckers preying on the grubs. Damage by woodpeckers searching for borer larvae can be substantial (Solomon 1969; Solomon and Morris 1971; Hay 1972; Hardin and Evans 1976). Borer-damaged trees will not yield high-quality veneer, furniture-grade lumber, or white oak barrel staves for the bourbon industry (Burns 1971b). Lumber is not significantly weakened by borer attacks and there is little growth loss (Abrahamson and McCracken 1971).

Incidence of attack varies with species. At 12 hardwood sawmills in Georgia's Piedmont, Ebel (1967) studied borer damage visible on the ends of logs of 13 species of pine-site hardwoods plus river birch (*Betula nigra* L.), sycamore (*Platanus occidentalis* L.), and cottonwood (*Populus deltoides* Bartr.). Damage was greatest in red maple and pignut hickory; ash and the oaks were intermediate in percent with defect, while hackberry, sweetgum, elm, and yellow-poplar were least damaged (table 11-5). Most of the damage was in the form of tunnels ranging in width from 1/4- to 3/4-inch. Smaller holes were prevalent, primarily in red maple, sycamore, and post oak––all host species of the Columbian timber beetle (*Corthylus columbianus* Hopkins).

TABLE 11-5.—*Insect-caused defect in log ends of 16 species of Piedmont hardwoods* (Ebel 1967)

Degree of damage and tree species	Logs examined	
	Total number	Percent with defect
Negligible		
Hackberry	54	2
Sweetgum	308	3
River birch	70	4
Elm (*Ulmus* sp.)	98	4
Yellow-poplar	328	4
Light		
Sycamore	109	17
Oaks, white (incl. post oak)	243	25
Oak, cherrybark	83	29
Oak, water	174	29
Moderate		
Cottonwood	89	30
Oak, southern red	245	41
Oak, scarlet	52	42
Ash (*Fraxinus* sp.)	143	43
Oak, northern red	116	47
Heavy		
Maple, red	144	78
Hickory, pignut	98	83

Ebel (1967) found injury in both butt and upper logs, but upper logs were more frequently damaged except in red maple and ash. The average number of borer holes visible on log ends of the attacked species ranged from 1 to 9; the volume of defective boards sawn was roughly proportional to intensity of attack.

Incidence of attack appears to vary greatly with geographic location. Bryan (1961) surveyed 1,000 sweetgum trees over 8 inches dbh in the Piedmont of the Carolinas and Georgia; one-third had insect damage on the butt log, much above Ebel's finding (table 11-5).

Value losses from degrade by trunk borers are substantial. Morris (1964) evaluated typical flooring and furniture logs from the Ozark National Forest in Arkansas and estimated value loss at $10 to $27 per thousand board feet of lumber sawn, as follows:

Species and use	Value loss per thousand board feet
	Dollars (1964)
Black oak	
Flooring	12.30
Furniture	11.61
Northern red oak	
Flooring	10.27
Furniture	27.08
Post oak	
Flooring	16.48
Furniture	—

Morris (1977) estimated that a sawmill cutting 10 million board feet of southern oak lumber annually, loses about $200,000 in value per year from degrade due to trunk borers. Readers needing additional information on trunk borer damage to Appalachian hardwoods will find data from Hay and Wootten (1955) and Donley (1974) useful.

Timber degrade of such magnitude calls for elucidation of its sources. Because the damage usually becomes evident only after logs are sawn into lumber or cut into veneer, identity of the responsible borers is sometimes difficult to establish. Oaks are particularly attacked by borers such as the carpenterworm, the red oak borer, and the white oak borer—all of which make holes 1/2-inch in diameter or larger. Smaller holes are made by ambrosia beetles, which attack red maple, yellow-poplar, and the hickories, as well as oak. The most important of these insects that degrade wood in living trees are described in the following paragraphs.

***Arrhenodes minutus* (Drury).**[8]—The **oak timberworm** is most damaging in trees larger than 5½ inches dbh. Preferred hosts are mature trees of the red and white oak groups—both living and recently dead. Adult beetles are dark reddish-brown to black and up to 1⅓ inches long. In late spring or summer, the female chews a cylindrical hole into exposed sapwood—often in wounds made by other trunk borers—and lays a single egg. Successful attacks are best identified by white powdery frass at the egg site. The larvae hatch in a few days and tunnel in all directions into sound wood. Each larva bores almost through the tree, and then reverses to bore back across the grain to the point of origin. They pupate in the gallery, emerging as adults through the enlarged hole at the egg site. Winding tunnels, from 1/100-inch up to 1/8-inch in diameter, characterize the damage in lumber (fig. 11-25).

***Corthylus columbianus* (Hopkins).**[9]—The **Columbian timber beetle,** a small borer, causes extensive flagworm defect in soft maple and spotworm defect in post oak; yellow-poplar and the elms, among other hardwoods, are also attacked. Periodic invasions during the life of a tree are overgrown, resulting in large volumes of degraded wood throughout the diameter of the trunk. Most attacks occur in the lower 8 feet of the stem, but some have been observed as high as 29 feet above ground. More damaging than the small gallery holes (1/32- to 1/16-inch in diameter) in lumber and veneer are the large associated blue-gray stains (fig. 11-26A) which give the defect its common names of flag-worm, worm-spot, steamboat, patchworm, grease-spot, and black hole. For cooperage, however, both the gallery holes and the stain are objectionable, especially in oak. One or two gallery holes may be sealed with wooden plugs and thus tolerated, and a small number of stained spots (flags) are allowed in lower quality cooperage. High-quality tight cooperage, however, excludes extensively stained wood. A stave company in Missouri estimates (1976) that 20 to 30 percent of the white oak logs they buy show evidence of attack by this insect; a stave loss of 5 to 7 percent results. Veneer manufacturers also lose heavily from the Columbian timber beetle because neither stain nor holes are tolerated in face veneer. Lumber with worm holes and stain from this pest sells at significantly lower prices than comparable sound lumber.

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[8] This description is taken from Donley and Terry (1977).

[9] The first paragraph under this heading is condensed from Oliveria (1976); the second is abstracted from Baker (1972).

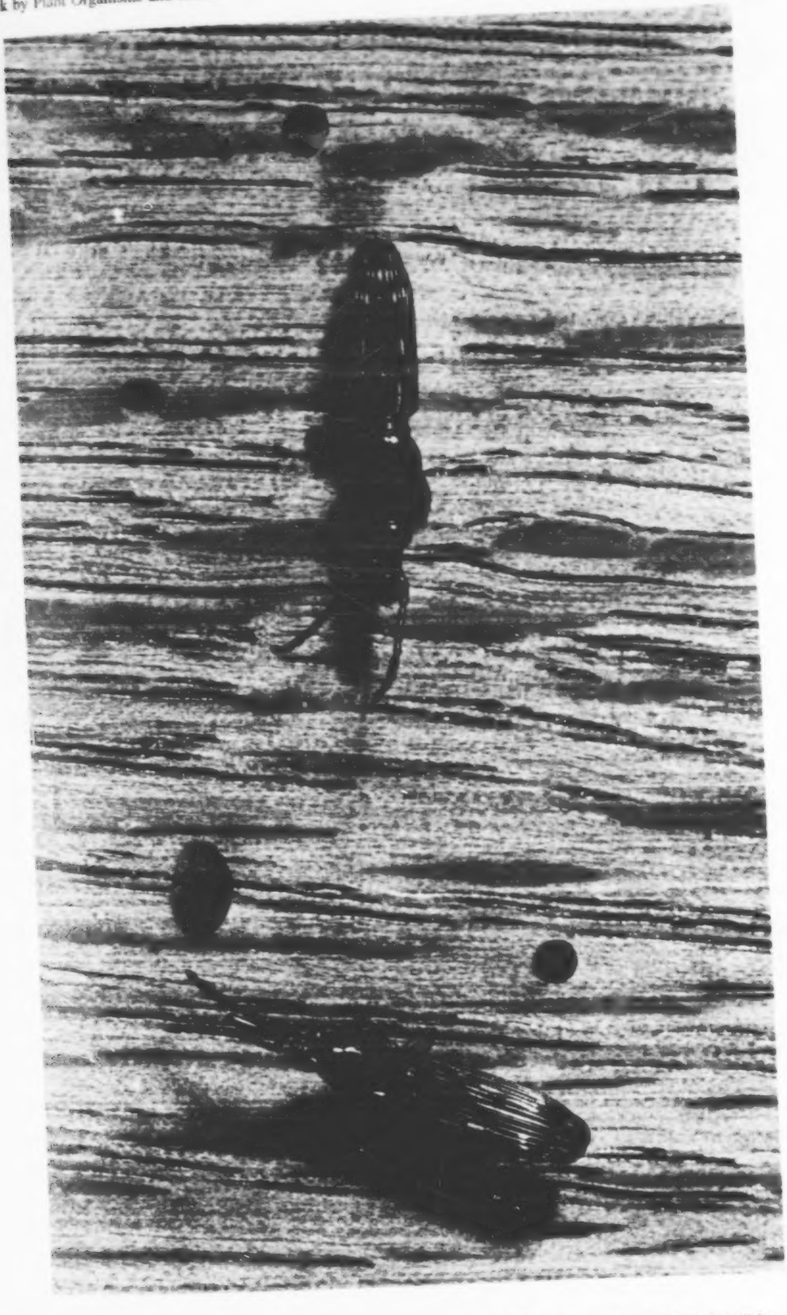

Figure 11-25.—A pair of adult oak timberworms on an oak board perforated with 3/16-inch circular holes made by the larvae. (Photo from Donley et al. 1969.)

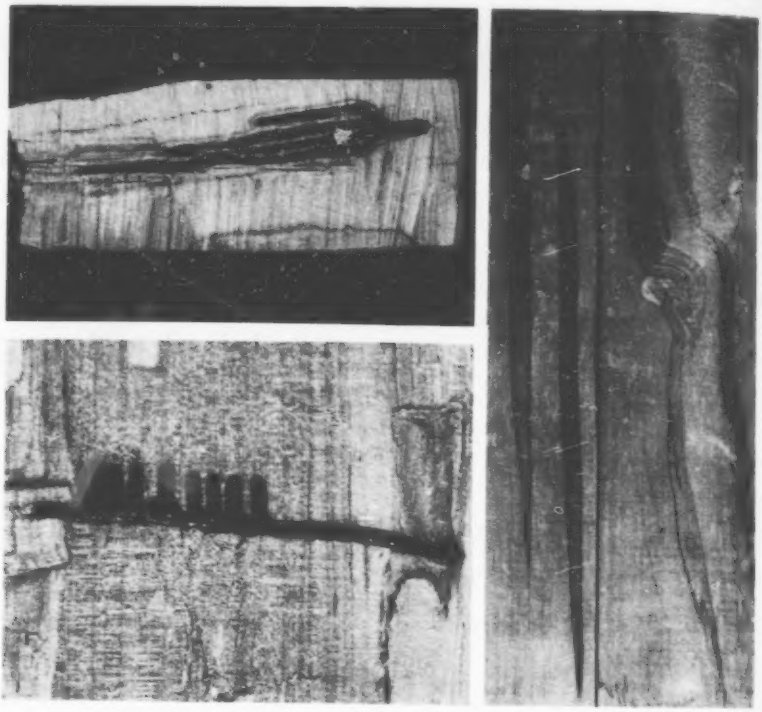

Figure 11-26A.—Galleries in red maple made by Columbian timber beetles, and associated stain. (Top left) Galleries—1/32- to 1/16-inch in diameter—viewed in tree transverse section, looking upward. (Bottom left) The same galleries viewed in tree longitudinal-radial plane; egg cradles (the branched galleries) are directed upward in the tree. (Right) Stain associated with beetle holes. (Photos from U.S. Dep. Agric. For. Serv. files of F. L. Oliveria and J. D. Solomon.)

Adult Columbian timber beetles are stoutish, black, and 1/16-to 1/8-inch long (fig. 11-26B). They become active in May and June in West Virginia, prefer vigorous trees, and tend to reattack host trees. Entering the wood through bark crevices, usually on the main trunk near the base, they bore straight into the sapwood nearly to the heartwood and then turn right or left; entrance holes are clean-cut and from 1/32- to 1/16-inch in diameter. From upper and lower tunnel surfaces they excavate short chambers where eggs are laid and larvae develop. The larval food is not wood, but a yeast of the species *Pichia* stored and transmitted by prothoracic mycetangia possessed by the male beetle. Winter is spent as pupae and adults in the galleries of last attack. There are two or three generations a year.

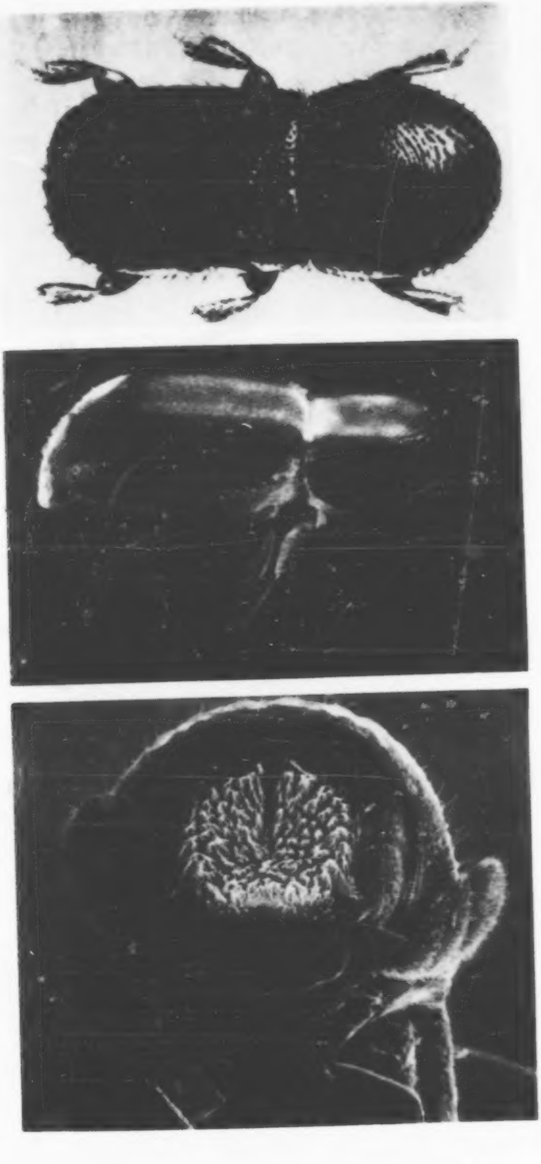

Figure 11-26B.—Adult Columbian timber beetle measuring about 1/8-inch long. (Top) Dorsal view. (Center) Lateral view. (Bottom) Ventral view of mouth and head. (Drawing at top after Baker 1972; micrographs from U.S. Dep. Agric. For. Serv. files of C. W. McMillin.)

***Enaphalodes rufulus* (Haldeman).**—Larvae of the **red oak borer**, a long-horn beetle, cause extensive damage to living southern oaks. In the Central States, northern red, scarlet, black, and white oaks are especially subject to attack (Abrahamson and McCracken 1971; Donley and Terry 1977). Baker (1972) describes the adult beetles as about 1 inch long and light brown with spots of lighter finer hairs (fig. 11-27). Eggs are deposited in the summer singly into bark crevices or beneath lichen patches on trees larger than 2 inches dbh. Young larvae bore directly into the phloem and feed during the first summer in cave-type burrows about 1/2-inch square. They winter in these burrows and feed on phloem in the spring, and in early summer bore obliquely upward in the sapwood and straight upward in the heartwood for 6 to 10 inches. They winter again as larvae and pupate the following spring. When 2 years old, adults leave the tree through 1¼- by ½-inch oval holes. New attacks are evidenced by granular frass and excelsior-like fibers pushed out from entrance holes, and wet spots caused by sap leakage (Baker 1972; Donley and Terry 1977).

***Goes Tigrinus* (De Geer).**—Larvae of the **white oak borer,** a long-horn beetle, bore into the heartwood of small white oak and post oak trees (less frequently into other oaks and hickories), making galleries averaging about ½-inch in diameter (fig. 11-28) and 5 to 10 inches long with separate entrance and exit holes. Accompanying stain (pore streaks) are up to 3 feet long (Donley and Terry 1977). Baker (1972) describes the adult as slightly more than an inch long, robust, dark brown, and irregularly covered with a dense coat of fine white hair, giving it a white and brown mottled appearance (fig. 11-28). Adults emerge in May and June and feed for a week or two on oak leaves and the bark of tender twigs. They deposit eggs in the trunks of young trees, usually 1 to 12 inches in diameter, or in the branches of larger trees. The larvae bore directly through the sapwood, and then penetrate upward deep into the heartwood. Full-grown larvae measure up to 1½ inches long. Their tunnels, up to ½-inch in diameter and 10 inches long, permit entry of decay fungi, especially when enlarged by woodpeckers (fig. 11-29). Toward the end of its last summer in the tree, each larva encloses itself in a chamber at the upper end of the gallery, where it rests until spring and then spends about 3 weeks in the pupal stage. The emerging adult gnaws a perfectly round hole through wood and bark to the outside. The life cycle requires 3 to 4 years (Solomon and Morris 1965; Baker 1972).

A related species that attacks hickory and pecan trees is the **hickory borer** (*Goes pulcher* Haldeman). Another related borer that attacks pine-site hardwoods, e.g., elms and black, cherrybark and water oaks, is the **living-beech borer** (*Goes pulverulentus* Haldeman). The biology and habits of these two trunk borers have been described by Solomon (1972, 1974).

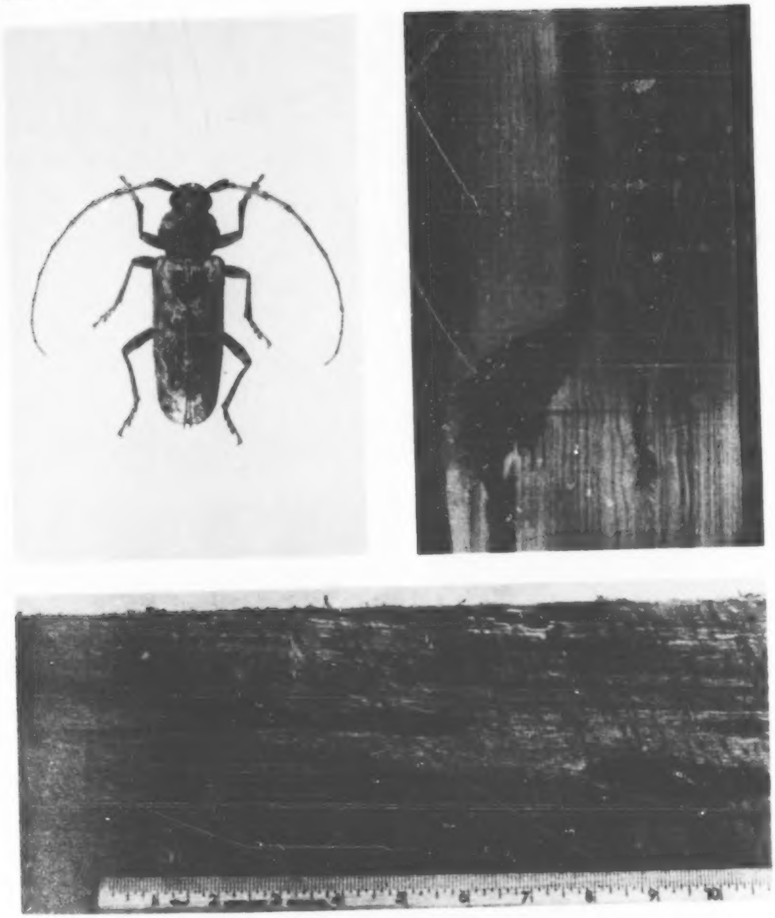

Figure 11-27.—(Top left) Adult red oak borer measuring about 1 inch long. (Top right) Red oak borer gallery in a sapling Nuttal oak (*Quercus nuttallii* Palmer). (Bottom) Oak board showing series of attacks; the scale shows inches. (Photos from files of J. D. Solomon and D. E. Donley, U.S. Dep. Agric. For. Serv.)

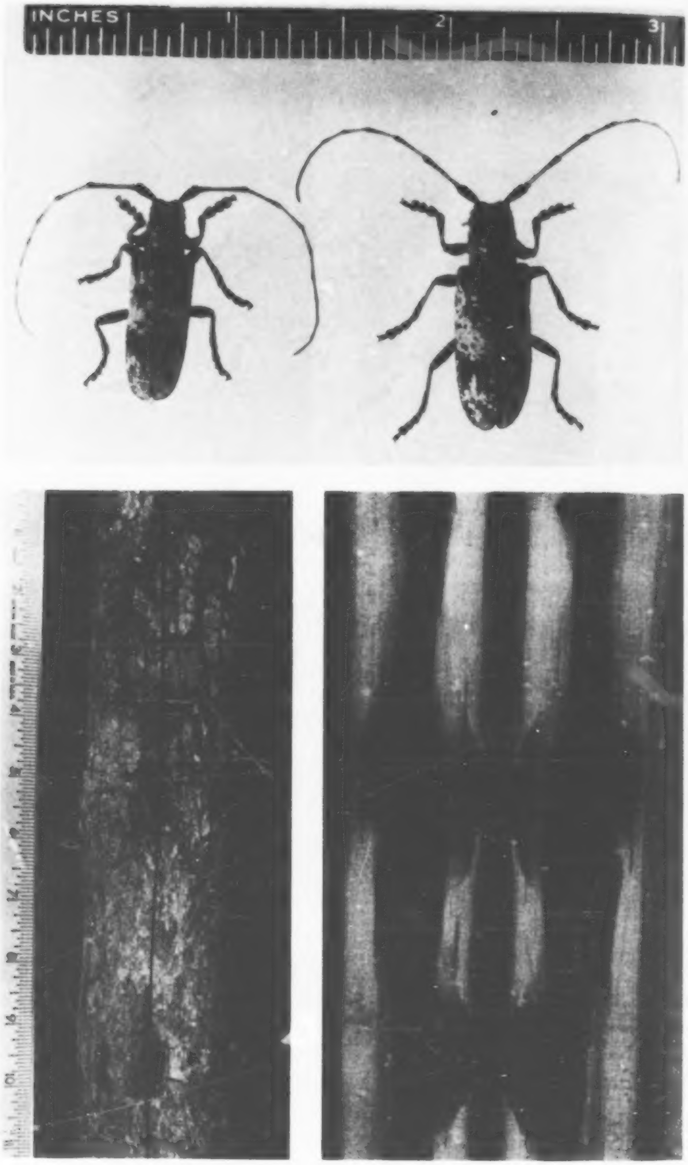

Figure 11-28.—(Top) Adult white oak borers; the male is on the left and the female on the right. (Bottom) The sapling on the left has open holes where woodpeckers removed borer larvae; at right is the sectioned sapling showing where rot entered the holes and ruined the tree. The scales are in inches. (Photos from Solomon and Morris 1965.)

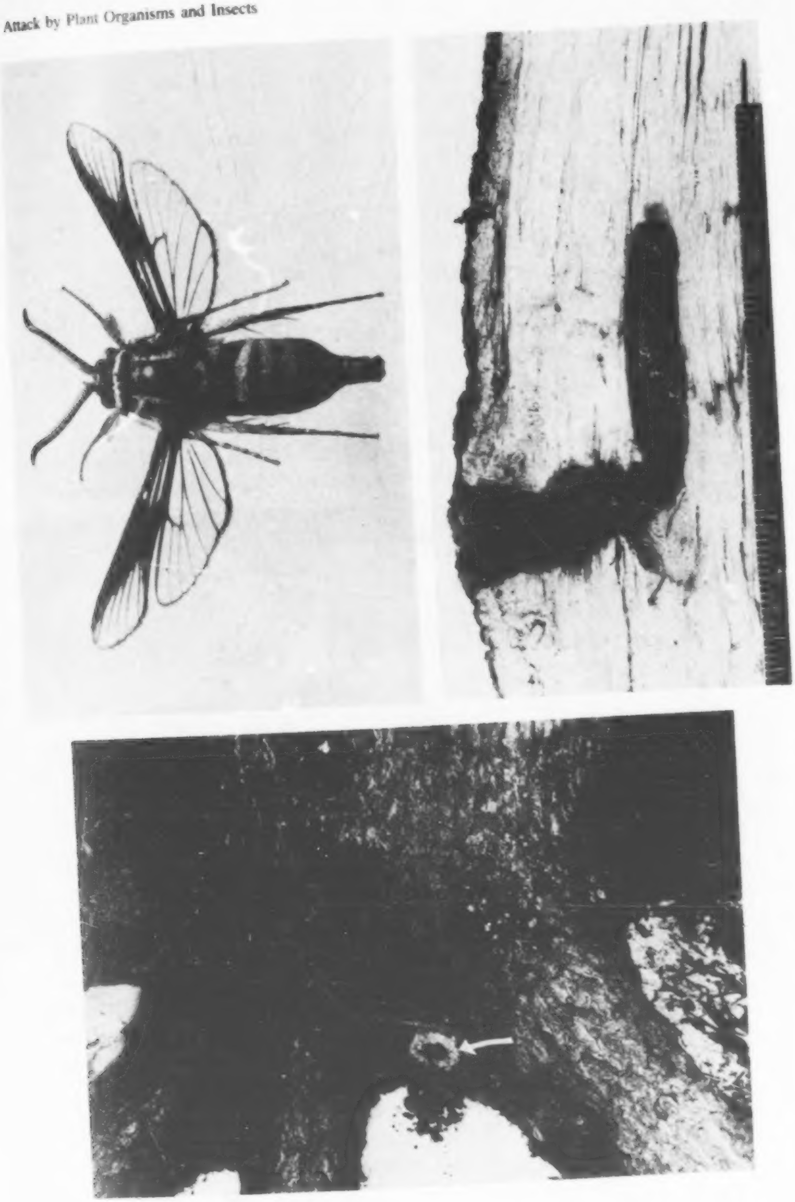

Figure 11-29.—(Top left) Adult female moth of *Paranthrene palmii* with 1.5-inch wing-spread. (Top right) Larva in gallery it has made. (Bottom) Borer attack at base of living oak tree; a pile of frass is below the entrance hole which has been ringed in white for photographing. (Photos from Solomon and Morris 1966.)

Paranthrene palmii **(Hy. Edw.).**[10]—Larvae of the **clearwing borer** tunnel into the base of oak trees (including cherrybark, Shumard, and black oaks) and tunnel upward, but seldom get above stump height. Entrance holes are 3/8- to 5/8-inch in diameter; galleries are up to 3/8-inch in diameter and 3½ to 4 inches long (fig. 11-29). Although few attacks enter the merchantable trunk, vacated galleries are frequently widened and lengthened by the carpenterworm, a more destructive borer, while fungi extend damage farther upward. The adult female moth has a wingspan of about 1½ inches; the male is slightly smaller. Both are orange and black and resemble a queen yellow jacket. The larvae are mostly pale purplish brown with black heads and yellowish brown thoracic shields. The eggs are probably laid in bark crevices at the base of the tree. Trees 12 inches dbh and larger are most heavily infested, and two to five attacks on a tree are common. In Mississippi no attacks have been found on trees smaller than 6 inches dbh. The life cycle of the insect is 2 years.

Podesesia syringae **(Harris).**—This clearwing moth, called the **ash borer,** tunnels in the branches and trunks of green and white ash. Solomon (1975) describes the adult moth as wasp-like in appearance and size (fig. 11-30). The thorax and abdomen are brownish black and marked with chestnut red; the legs, banded with chestnut red and black, become yellowish distally. Wingspan of the adult varies from 28 to 35 mm in females and 24 to 32 mm in males. The eggs are light brown, elliptical, and about 0.8 mm long and 0.4 mm wide. The larvae are white except for amber-colored head, thoracic shield, and spiracles. The pupa is reddish brown and 18 to 24 mm long (fig. 11-30).

In Mississippi, Solomon (1975) observed emergence of the moths from mid-March to mid-July, and in October; they appear earlier and are active later in the South than in the North. Females normally mate soon after emergence, and promptly oviposit eggs singly and in clusters. Incubation requires 9 to 13 days; first evidence of larval attack is sap mixed with fine frass oozing from small bark openings. Young larvae first mine 1 to 3 cm laterally and 2 to 5 cm vertically in the bark, then radially into the sapwood 2 to 4 cm, then upward for varying distances, and finally back to the surface. Completed galleries are 5 to 7 mm in diameter and vary from 7 to 32 cm long. Although galleries commonly interlace in heavily infested boles, only a single larva is found in each.

Prior to pupation, the gallery is extended almost to the bark surface, except for a paper-thin cover, and the passage is tightly plugged with wood chips and frass. After about 3 weeks the adult exits through a 4- to 5-mm, perfectly round hole (fig. 11-30).

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[10] Text under this heading is condensed from Solomon and Morris (1966). A selected bibliography of the clearwing borers has been provided by Solomon and Dix (1979).

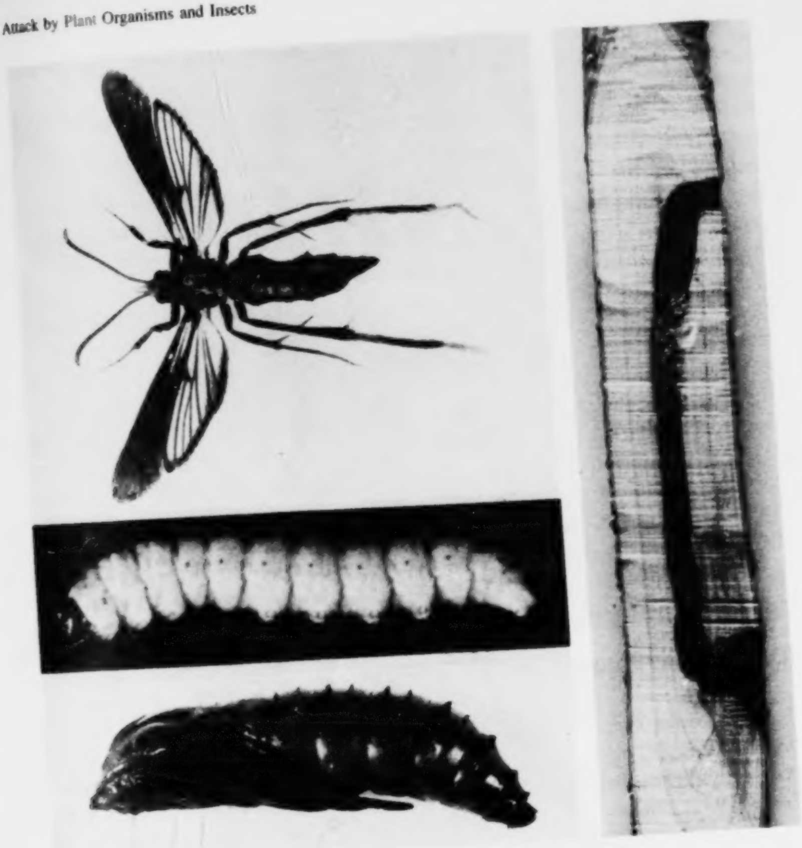

Figure 11-30.—Ash borer. (Top left) Adult female of *Podosesia syringae* (Harris) with 1.2-inch wingspan. (Center left) Nearly full-grown larva about 1 inch long. (Bottom left) Pupa. (Right) Larval gallery in 1.3-inch-diameter green ash sapling. The gallery extends inward, upward, and back to surface; upper portion of gallery contains pupal chamber plug. (Photos from Solomon 1975.)

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***Prionoxystus robiniae* (Peck).**[11]—The **carpenterworm** which particularly attacks trees of the red and white oak groups but also elms, green ash, and maples among pine-site species, is probably the most important borer of Mid-south oaks (Abrahamson and McCracken 1971). The adult carpenterworm is a dark, gray-mottled, stout-bodied moth. The female is lighter colored than the male and considerably larger—with wingspread of about 3 inches. Full-grown larvae are about 2½ inches long, and are greenish white with shiny brown heads armed with black mandibles (fig. 11-31). Moths appear in late April in the South, and the female deposits upwards of 450 to 800 eggs in groups in bark crevices, near wounds, or under vines, lichens, or moss. Young larvae bore directly to the inner bark and feed there until about half grown. Then they bore into the wood, their tunnels angling upward in the sapwood and straight upward in the heartwood (fig. 11-31). Feeding may be finished in 1 year in the Deep South but may continue for 3 or 4 years in the North. Tunnels are kept open and may eventually reach a diameter of nearly 3/4-inch and a length of 15 inches. Mature larvae line their tunnels with loose, silky, yellowish-brown webs. They pupate at the upper end of the tunnel, but wriggle to the tunnel mouth before completing transformation to adults. After the adult's emergence, the pupal case usually remains in place, the head and thorax sticking out. Solomon and Hay (1974) have provided an annotated bibliography of this destructive insect.

IDENTIFICATION OF TRUNK BORERS

A key to frass characteristics of certain trunk borers, including the red oak borer, the white oak borer, the clearwing borer, and the carpenterworm, has been provided by Solomon (1977c). Also, the color photographs by Donley and Terry (1977), illustrating oak stems under attack by the oak timberworm, the red oak borer, the white oak borer, and the carpenterworm, should be useful in identifying these pests in action.

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[11] The text under this heading is condensed from Hay and Morris (1961) and Baker (1972).

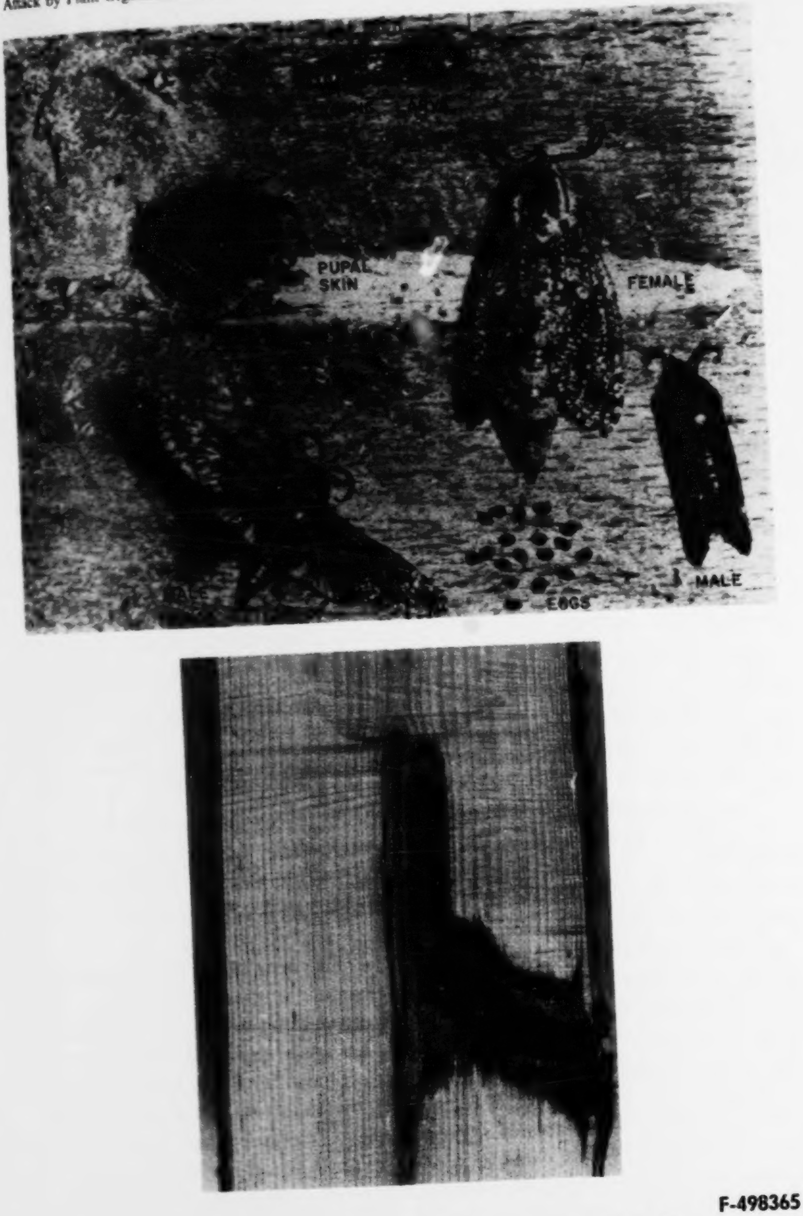

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Figure 11-31.—(Top) Life stages of the carpenterworm. (Photo from Hay and Morris 1961.) (Bottom) Stained wood around typical carpenterworm gallery in a 6-inch-diameter green ash sapling. (Photo from Solomon and Toole 1971.)

SILVICULTURAL CONTROL OF TRUNK BORERS

Solomon (1977a) suggested a number of silvicultural practices that create conditions unfavorable to pest insects. Although hardwoods on southern pine sites are not usually intensively cultured, the practices suggested give insight into the control problem:

- Fit tree species to the site; trees on sites sub-optimum for their species grow poorly and are often seriously damaged by insect borers.
- Favor tree species least favored by borers.
- Keep trees growing vigorously.
- Identify and remove brood trees harboring boring insects.
- Consider vine control on tree trunks in high-value stands.
- Harvest when trees are physiologially mature.
- Prevent tree injuries or hold to a minimum during harvesting or other operations
- Exercise caution with water management in timber stands.
- Salvage promptly after severe tree stress from prolonged drought, unseasonal flooding, fire, and storm damage.

11-8 TERMITES

Termites are wood-destroying, soft-bodied social insects having two pairs of similar wings. The species classed as subterranean termites and drywood termites are those of economic importance to the geographic areas comprising the major markets for pine-site hardwood products, i.e., the Southern, Eastern, and Central States.

The four subterranean termite species particularly damaging to southern hardwood products all belong to the family Rhinotermitidae. Three are in the genus *Reticulitermes*, *R. Flavipes* (Kollar), *R. virginicus* (Banks), and *R. hageni* Banks; and one—the Foromosan termite—is of the genus *Coptotermes*, i.e., *C. formosanus* Shiraki.

Drywood termites are members of the family Kalotermitidae. They are distinguished from subterranean termites not only by their larger size but also by their ability to establish colonies and live in undecayed wood having little moisture; they require no contact with the ground. In the South, drywood termites cause substantial damage, but much less than subterranean termites. In the areas in which pine-site hardwoods are utilized, the most important species of drywood termite is probably *Incisitermes snyderi* (Light). This termite has a range from South Carolina to Florida, west to eastern Texas. A second drywood termite of substantial economic importance in southern coastal areas—particularly southern Florida—is *Cryptotermes brevis* (Walker).

None of these termites cause significant damage to living hardwood trees, but all damage hardwood products in the United States—and the cost of protective treatments for their control totals many millions of dollars annually. For discussion of their economic impact, description and life cycle, detection and control, the reader is referred to pages 665 through 686 of Agriculture Handbook 420 (Koch 1972).

NATURAL RESISTANCE TO TERMITES

Discussion of termites in this text is limited to ranking 22 of the pine-site hardwoods according to their resistance to the subterranean termite *Reticulitermes flavipes* (Kollar). For this purpose, Carter et al. (1976) sampled 9 or 10 trees in each of the species (table 11-6). Trees 6 inches dbh were selected as most typical of hardwoods growing on southern pine sites; their average age was 39 years. Test bocks (2.0 by 2.0 by 0.9 cm along the grain) were taken from outer heartwood 6 feet above ground level. Where heartwood zones were too narrow, as in white and green ash, blocks were cut to include as much heartwood as possible. In trees without visible heartwood, blocks were cut from the inner third of the radial distance to the bark. Plastic containers 5.0 cm in diameter by 3.5 cm high were packed with 50 g of sterile sand moistened with distilled water to maintain relative humidity near saturation. A weighed test block was placed on the surface of the sand of each container and 100 termites were added. The containers were placed in an incubator, and after 8 weeks at 25°C the live termites were counted and the wood blocks dried and reweighed to estimate the amount of wood eaten. This loss in weight was the index of termite feeding preference indicated in table 11-6.

TABLE 11-6.—***Wood consumed and termites surviving after 8 weeks exposure of 2.0 × 2.0 × 0.9 cm blocks to attack by 100 termites***[1] (Carter et al. 1976)

Species[2]	Wood eaten[3]	Species[2]	Termite survival at 8 weeks[3]
	Mg		*Percent*
Winged elm	131	Post oak	<1
Post oak	169	Winged elm	<1
Yellow-poplar	176	Black oak	2
Black oak	189	White oak	2
White oak	189	Southern red oak	4
Southern red oak	214	Blackjack oak[4]	7
Northern red oak	262	Yellow-poplar	10
Shumard oak	274	American elm	16
Scarlet oak	280	Northern red oak	17
American elm	288	Hickory, true	17
Cherrybark oak	306	Sweetbay[4]	22
Laurel oak	317	Black tupelo	23
Blackjack oak[4]	317	Laurel oak	25
Hickory, true	318	Scarlet oak	30
Sweetbay[4]	319	Shumard oak	31
Black tupelo	323	Water oak	31
Sweetgum	326	Green ash	32
Water oak	326	Cherrybark oak	32
Green ash	369	Sweetgum	34
White ash	379	White ash	35
Red maple	400	Red maple	38
Hackberry	530	Hackberry	72

[1] See text for test conditions.

[2] Ranked from most resistant to most susceptible; means connected by a line are not significantly different at the 0.05 level of probability (Duncan's multiple range test).

[3] Wood consumption and termite survival data were transformed to arc sine for analysis but are presented as retransformed data in the table.

[4] Nine rather than 10 trees tested.

In this test of Carter et al. (1976), hackberry was the only wood of which more than 500 mg were eaten. Of the non-oak species, winged elm and yellow-poplar were the most resistant to attack by termites. Of the 11 species of oak tested, 10 were among the 13 species with the least wood eaten. The most susceptible of the oaks was water oak, but feeding on it did not differ significantly from that on blackjack, laurel, cherrybark, scarlet, Shumard, and northern red oaks. Less than 10 percent of the termites survived on the two white oaks (white and post) and on three red oaks (black, southern red, and blackjack). Most of the wood species, when ranked by survival and amount of wood eaten by *R. flavipes*, fell generally into broad, overlapping groups (table 11-6).

Decay versus termite resistance.—Two species—post and white oaks—were quite resistant to both decay fungi (table 11-1) and termites (table 11-6); two species—red maple and hackberry—were susceptible to both. In the other species resistance to the test organisms appeared unrelated. For example, blackjack oak was the most resistant to decay, but its mean weight loss to termites was 317 mg. In contrast, winged elm and yellow-poplar were quite resistant to termites but quite susceptible to decay.

TERMITE RESISTANCE OF RECONSTITUTED PRODUCTS

The susceptibility of unprotected particleboards to termite attack depends on the woods used (Becker 1972). Tests by Behr and Wittrup (1969) indicated that particleboards made from decay- and termite-susceptible wood such as jack pine (*Pinus banksiana* Lamb.) sapwood can be protected by adding flakes of resistant redwood (*Sequoia sempervirens* (D. Don) Endl.) or northern white-cedar (*Thuja occidentalis* L.) heartwood. Since the oaks as a group (particularly post and white oaks) appear fairly resistant to both termites and decay fungi, Carter et al. (1976) concluded that flakes of these species should increase the finished product's resistance to biodegradation. They felt that the potential is good for using pine-site hardwoods in particleboards.

Treatments to protect reconstituted products from termites and decay are described in chapter 21.

11-9 PRODUCT DAMAGE BY OTHER WOOD-INFESTING INSECTS

Hardwoods from southern pine sites when converted into logs, pulpwood, and lumber may be attacked by numerous wood-infesting insects other than termites; additionally, molding, flooring, and furniture may be attacked in use—if exposed in a damp environment.

LOGS, PULPWOOD, AND GREEN LUMBER

Infestations by trunk borers previously discussed can be eliminated by proper kiln-drying. If felled logs are promptly sawn and the lumber is immediately kiln-dried and used, infestations from insects that attack logs and green lumber may be avoided. When logs, pulpwood, and green lumber must be stored for prolonged periods, such products may be attacked by various insects such as clearwing borers, ambrosia beetles, banded ash borers, and certain other roundheaded borers or flatheaded borers. Discussions of these pests follow in paragraphs arranged in alphabetical order by species name.

The oak timberworm, already discussed (fig. 11-25) may also attack ends of stored logs or log surfaces from which the bark has been removed. Its larvae bore into the wood, increasing the diameter of their tunnels as they grow. These tunnels permit the entry of stain and rot fungi. Damage usually is not great in logs stored for short periods (Morris 1974).

***Platypus* sp.**—The family Platypodidae is represented in the United States by seven species of the genus *Platypus* (Arnett 1963). Of these, two especially attack southern hardwoods. *P. quadridentatus* (Oliv.) particularly attacks oaks, while *P. compositus* (Say) breeds in a wide variety of hardwoods including pine-site hickories, oaks, elms, and sweetgum. These **ambrosia beetles** attack weakened or dying trees, freshly cut hardwood logs, and unseasoned hardwood lumber. Logs can be attacked within 24 hours after felling and bucking (Morris 1974). Heaviest attack occurs during July and August (Snyder 1941). The adults are reddish-brown, elongated beetles approximately 1/4-inch in length. They bore into the sapwood and heartwood of logs or lumber, making pin-size holes—dust-free and 0.8 to 1.3 mm in diameter—darkly stained by an ambrosia fungus upon which the adults and larvae feed.The female lays eggs in small clusters in the tunnel, and the developing larvae excavate small cells extending from the tunnel parallel with the grain of the wood (fig. 11-32). There are several generations each year. Small piles of fluffy boring dust accumulate around the base or in bark crevices of infested trees, stumps, and logs. In lumber the pin-size holes surrounded by black stain are characteristic (Baker 1972).

***Neoclytus acuminatus* (F.)**—The **red-headed ash borer** deposits its eggs in and on bark of ash and other hardwood logs, and the larvae tunnel into the wood (Baker 1972). Only logs with bark are attacked, but the larvae may continue their development in sawed wood and may emerge as adults months later and many miles from their origin. Some have emerged in Portugal from lumber cut in Arkansas and shipped from New Orleans, La. (Morris 1974).

Baker (1972) gives a brief description of the insect and its biology. The adult is about 15 mm long. The head and thorax are reddish; the body is light brown with the apical part of the elytra sometimes much darker. The elytra are also marked with four transverse bands of fine yellow hairs and the middle and hind legs are long and reddish. Adults become active by mid-February in the Deep South and progressively later until May or June in the North. Eggs are deposited beneath the bark of dead, unseasoned wood. The larvae first feed beneath the bark, then tunnel into the sapwood and often reduce it to powder. In the South there are several generations per year; in the North only one.

***Neoclytus caprea* (Say).**—The **banded ash borer** attacks ashes, hickories, elms, and, rarely, white oak, among pine-site hardwoods. Adults are long-horned, dark-brown to almost black and 12 to 25 mm long.They have a line of fine, white or yellowish hairs on the thorax and four bands of the same material and color across the elytra; the first two bands meet, almost forming circles. Adults emerge in early spring and deposit their eggs in bark crevices. Ash logs cut during winter are especially subject to attack. The larvae feed for a while under the bark before boring into the sapwood to feed during the summer, and pupate in the fall; adults emerge the following spring. There is normally one generation per year, but if the wood is sawed, stored, and dried, the life cycle may require several years. Ash products that retain their bark may be literally honeycombed with tunnels tightly packed with frass. Bark should therefore be removed from the edges of boards or from logs in cabins subject to attack by these longhorn beetles.

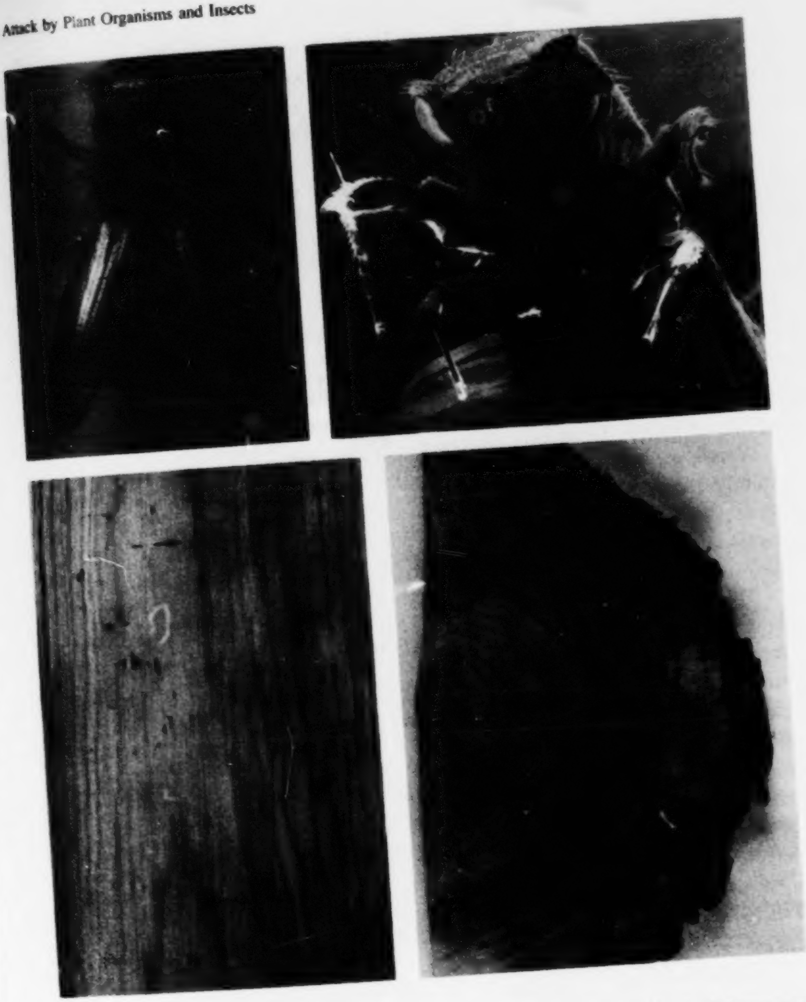

Figure 11-32.—Ambrosia beetle. (Top, left) Dorsal view, elytra spread, of adult measuring about 4 mm long. (Top right) Ventral view of head and thorax. (Bottom left) Holes (1/32-inch-diameter) in lumber viewed transverse to gallery showing black stains surrounding holes in willow oak (*Quercus phellos* L.). (Bottom right) Beetle galleries viewed in tree transverse section. (Beetle photos from files of C. W. McMillin; damage photos from J. D. Solomon, U.S. Dep. Agric. For. Serv.)

Xyleborus sp.—These **ambrosia beetles'** tiny holes in white oak are nearly invisible, but they ruin wood for use as bourbon staves. The genus *Xyleborus* Eichhof is represented by 17 species in the United States and Canada. Baker (1972) describes three among these that particularly attack the hardwood species that grow on pine sites; they breed in dying, unhealthy, or weakened trees as well as in felled trees and stored logs, as follows:

Ambrosia beetle species	Pine-site host species
X. affinis (Eichh.)	Oaks, hickories, sweetgum, hackberry
X. celsus (Eichh.)	Hickory
X. ferrugineus (F.)	Oaks, hickories, ashes, sweetgum

Adults are reddish brown and slightly smaller than ambrosia beetles of *Platypus* sp. Galleries are similar to those shown in figure 11-32 but vary with species in mode of gallery branching (Baker 1972).

Xylobiops basilaris **(Say).**[12]—A **false powder post beetle,** *X. basilaris*, family Bostrichidae, commonly attacks sapwood of recently felled or dying trees, logs, or limbs with bark. Hickories are particularly susceptible, but other hardwoods are also degraded by this insect. Damage consists of circular holes 3 to 9 mm in diameter and irregular longitudinal tunnels filled with frass or dust.

The beetle is basically black and 3 to 5 mm long (fig. 11-33 top). The adult bores through the bark and tunnels across the grain just under the wood surface, often girdling limbs or small trunks. Eggs are deposited at intervals along the sides of the tunnel. The larvae feed mostly in the sapwood, but also to some extent in heartwood. Their mines run parallel with the grain and are packed with fine, white, powder-like dust (fig. 11-33 bottom). The winter is spent mostly as mature larvae. Feeding may continue until the wood is quite dry. Adults often emerge after the wood has been processed, causing serious damage to such products as shuttle blocks, mallets, and mauls.

PROTECTION OF LOGS AND PULPWOOD

Prolonged storage of southern hardwood as logs or bolts requires protection against both insects and decay. The literature relates mainly to sawlogs. Hardwood pulpwood is probably harder to protect because of the greater surface area of pulpwood per unit of wood volume. Protective strategy for sawlogs calls for good yard sanitation and quick inventory turnover. For extended storage, logs must be chemically sprayed or continuously wetted with water.

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[12] Text under this heading is condensed from Baker (1972).

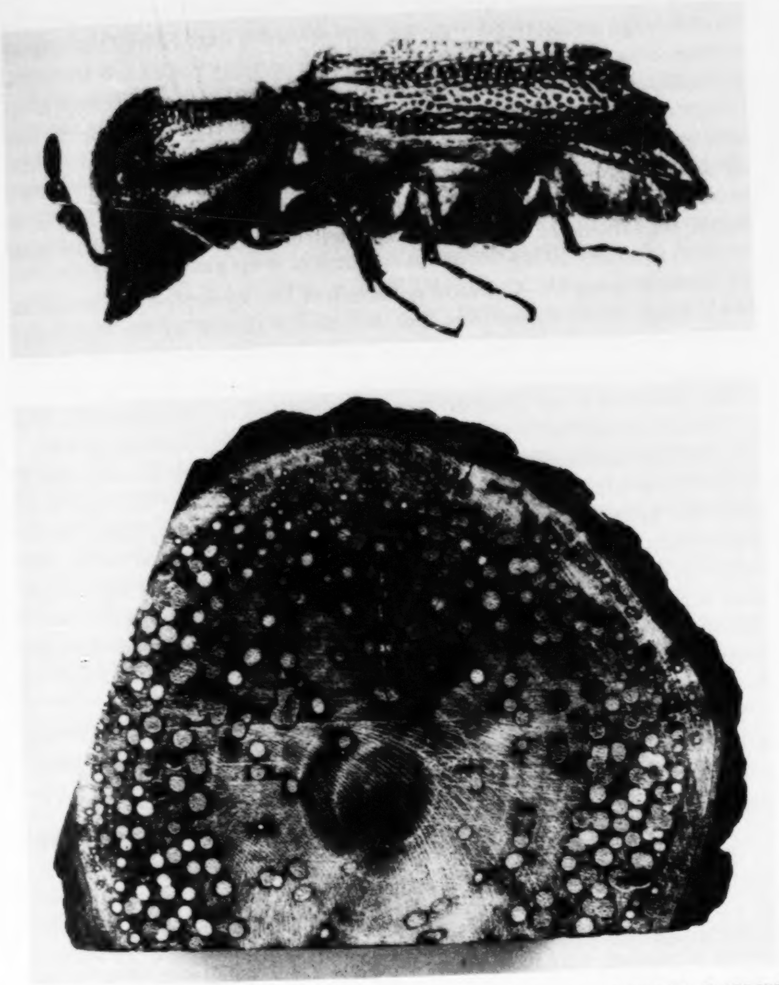

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Figure 11-33.—***Xylobiops basilaris***, a false powder-post beetle. (Top) Adult, about 4 mm long. (Bottom) Frass-filled tunnels due to larvae, in persimmon. (Photos from Baker 1972).

Yard sanitation and inventory control.—Morris (1974) concluded that insect damage is minimized if the log storage yard is near the mill log deck but with room for efficient movement; it should be properly graded and drained for all-weather use. Surfaces should be concrete or gravel with hard-surface alleys for loading machines. Trash should be removed by sweeping or scraping, then piled and burned, or buried; discarded logs should be promptly removed from the storage yard. In the warm season, logs should be stored no longer than 2 weeks; old logs should be sawed first. If protection for longer periods is required, logs should be sprayed with appropriate chemicals or put under water sprinklers (Morris 1974).

Chemical sprays.[6]—Chemical protection of logs by applying an insecticide and a fungicide to log surfaces was extensively studied by the U.S. Forest Service between 1930 and 1955. The most effective chemicals found then included the insecticide lindane (the gamma isomer of benzene hexachloride)—usually dissolved in no. 2 fuel oil, and the fungicide pentachlorophenol in oil or its sodium salt (sodium pentachlorophenate) in water solution (Scheffer 1969).[6] The principal disadvantage of chemical protection is the need in warm weather to treat soon after logs are cut—sometimes within 24 hours. The insecticide spray has given good protection againt borers in sweetgum, oaks, yellow-poplar, elms, and hickories (Scheffer 1969). Extended protection by fungicide spray of certain species, e.g., black oak and hackberry, against stain has not been accomplished (Scheffer 1969), and Kramer (1954) observed that oak logs—both red and white—sprayed with fungicide developed more stain than sweetgum or black tupelo. Fungicide spray of insect infested logs will not control stain (Scheffer 1969).

Scheffer (1969) found that a chemical spray to protect decked hardwood logs in the South against pinhole and larger wood borers—with some stain protection—could be prepared from solution in 100 gallons of no. 2 oil of the following chemicals.[6]

3½ pounds of the gamma isomer of benzene hexachloride (lindane)
24 pounds of pentachlorophenol

He observed that all log surfaces must be thoroughly wetted with the solution—preferably within 24 hours of felling. Kramer (1954) found that about 3½ gallons of solution were required per thousand board feet of logs (International 1/4-inch log rule) and that spraying of long-length logs was unduly costly in time and chemicals; decked short logs could be sprayed with a portable sprayer at a rate of about 7,000 board feet per hour; sprayer pressure used was 200 psi.

Stain in hackberry lumber sawn from trees felled in July near Vicksburg, Miss. was studied by Wagner et al. (1977). They found that trees felled and bucked in a single day, transported to the mill for thorough wetting (within 24 hours of felling) in a solution of sodium pentachlorophenate in water, and sawn after 4 weeks of storage yielded lumber having value $60 per thousand board feet greater than lumber from untreated control logs sawn on the same schedule.[6] Even so, these summer-cut sprayed logs had substantial blue-stain damage. The chemical solution contained one pound of 40 percent commercial sodium pentachlorophenate for each two gallons of water.[6]

In cool weather, Johnston (1952) found that storage may be extended to 3 to 4 months on hardwood logs and small bolts that have been sprayed with fungicide and pesticide.

Water spray.—Submersion of hardwood logs in water ponds will halt attack by borers and sapstain fungi; if logs float, however, portions exposed to air will dry, check, have access to oxygen, and suffer attack. The expense of ponding logs is so great that the practice has been virtually abandoned in the South. Instead, sawmill log yard managers have installed water sprinklers to wet logs in storage decks containing up to 1.5 million board feet (fig. 11-36). Details of such sprinkler and water spray systems are discussed and illustrated in Agriculture Handbook 420 (Koch 1972, p. 738-741). To be most effective all log surfaces and ends must be wet continuously. In Wagner's (1976) survey of southern log yards, managers estimated that logs—both southern pine and hardwood—could be stored for 6 to 18 months without appreciable damage.

Carpenter and Toole (1963) studied the protection afforded logs of sweetgum, hackberry, species of the red oak group, and cottonwood under water spray in Helena, Ark. The logs, cut less than 2 weeks earlier, were put into storage July 18, 1962 and remained under observation for 16 weeks. If continuously sprayed, logs were practically free of sapstain; hackberry had the greatest tendency to stain. Matched dry-stored logs were badly stained. Effectiveness of the water spray treatment in preventing ambrosia beetle attack could not be established; although the wetted logs were borer-free, the dry-stored control logs also escaped serious damage from these borers. The issue is not clear; in a study in southern Mississippi, continuous water spray of sweetgum logs failed to prevent serious ambrosia beetle attacks during 6 months of storage (U.S. Department of Agriculture, Forest Service 1963). Literature on the subject is scarce; it appears that the effectiveness of water spray on hardwood logs is not yet fully elucidated.

PROTECTION OF GREEN LUMBER[6]

Kiln schedules commonly used for lumber and veneer kill ambrosia beetles and sapstain fungi; kiln-dried hardwoods, if kept dry, are safe from attack by these agents. Where hardwood lumber is to be air-dried, risk of ambrosia beetle attack can be reduced by end-racking it for 8 to 15 days, to reduce its moisture content, before placing it on sticks for further air-drying (Snyder 1941).

Research indicates that green lumber can be protected from ambrosia beetles and sapstain while air-drying by dipping it in a water emulsion of benzene hexachloride containing 5 oz. of gamma isomer (lindane) per 50 gal. of water (Johnston 1952), to which an appropriate fungicide has been added.[6] See table 22-6, p. 1100-1101 of Agriculture Handbook 420 (Koch 1972) for a listing of fungicides that have been utilized.

Powder post beetles of the family Lyctidae (to be described under the next heading) attack ring-porous hardwood species such as the oaks, ashes, and hickories. Johnston et al. (1955) and Smith (1968) observed that a green-lumber dip in the lindane formulation just described will prevent lyctid beetle attack in rough dry lumber that is stored for extended periods.[6] Green lumber dips are surface treatments, however, and if the lumber is planed or machined, another treatment is needed to protect against lyctid beetles.

DRY LUMBER AND WOOD IN USE

Damage by insects other than termites to southern pine wood in use is primarily to structures, for example, to joists in crawl spaces under southern homes. Annual losses from such damage, and expenditures to control or avert damage, total many millions of dollars annually. For a discussion of these losses and of treatment incidence, the reader is referred to Williams and Smythe (1978, 1979).

Hardwoods are little used as structural material in southern residences. Damage to hardwoods by these wood-infesting insects is therefore mainly in manufactured products such as furniture, implements, and flooring and millwork in buildings.

The insects that attack dry hardwood bore small holes—mostly smaller than 1/8-inch in diameter, although some (Bostrichidae) may bore holes as large as 3/8-inch in diameter. Attacks by insects such as the Bostrichidae, Lyctidae, and flat oak borer are most likely to occur when hardwoods are being processed, manufactured, or stored. Anobiidae may infest these woods during storage, but attacks after wood is in use would occur only if the wood is exposed in a damp environment.

Williams (1980) concluded that changes in wood processing and use have influenced the likelihood of beetle infestations in seasoned wood. He found that fewer houses are being built with crawl spaces and more houses have central heating and air-conditioning, so the number of anobiid beetle infestations should decline. The likelihood of lyctid infestations in domestic hardwoods has been decreased by improved processing and marketing, but increased imports of tropical hardwoods likely will increase the frequency of infestations. More imports of unseasoned hardwood crates, pallets, and dunnage also may increase the probability of bostrichid infestations. Incidence of infestations by old house borers probably will change little. Trends in wood use suggest the present nationwide incidence of wood-destroying beetle infestations in structures ranks: anobiids, lyctids, old house borers, and bostrichids. Rankings of anobiids and lyctids, however, probably will be reversed in the near future. Lyctids already create the greatest replacement expense.

Anobiidae.[6]—Williams (1973a) describes case studies of attacks by *Xyletinus peltatus* (Harris) in which hardwoods were infested. One case involved use of insect-inhabited wood from demolished buildings in the structure of a church; oak church pews and other woodwork were infested and damaged. In another attack, dry yellow-poplar molding stored in a barn was badly damaged; an average of 144 larvae per square foot were counted. In another case (Williams 1973b), anobiids moved from a moist crawl space into furniture of preferred hardwoods, such as yellow-poplar and hackberry, and caused significant damage.

An illustrated description of anobiid beetles is given on pages 705-711 of Agriculture Handbook 420 (Koch 1972) and will not be repeated here. Larvae tunnel within the wood; entrance holes less than 1/16-inch and exit holes about 1/8-inch in diameter and scattered randomly on the wood surface are external evidence. Over 200 holes in 1 square foot have been found on timber surfaces. Diffuse-porous hardwoods such as yellow-poplar are very susceptible to attack by anobiids; freshly sawn dry hardwood is attacked—but attacks usually are not detected until wood has been in use for 10 or more years (Williams 1973b).

Williams (1973bc) discusses identification of wood destroying beetles and their control. He suggests that anobiid infestations detected early in crawl spaces under houses can be controlled with relatively inexpensive thorough surface treatments with insecticides such as 0.5 percent water emulsion of lindane.[6] Hardwoods usually come under attack when infestations are widespread. When infestations are widespread and hidden in walls, then expensive fumigation is the only immediate solution. Even fumigation is risky because some fumigants such as methyl bromide cause odors on certain rubber-based materials, and other fumigants such as sulfuryl fluoride have unknown effectiveness against beetle eggs.[6] Movable objects such as lumber, furniture, or implements can be fumigated in a vault or vapor-proof plastic bag.

Bostrichidae.—These insects, commonly called **false powder-post beetles**, measure from 1/8-inch to 1 inch in length and are generally dark brown to black in color and cylindrical in shape. Their length and shape differentiate them from lyctus beetles—the true powder-post beetles—which are about 1/6-inch long and have flat bodies. Unlike lyctus and anobiid beetles, which lay their eggs on wood surfaces or in crevices, most bostrichid beetles lay eggs in tunnels they bore through the bark or in pores connected to these tunnels. Figure 11-33 and related earlier text more fully describe one species—*Xylobiops basilaris* (Say), and its mode of attack. The bostrychids attack only freshly felled and manufactured wood, but infestations continue until wood is very dry. Since most species require bark for egg-laying, they do not reinfest manufactured wood products.

Bark removal prevents attack by most species. Others, however, may bore for egg laying, even if the surface is sealed. Williams (1973b) suggests that if the infestation is small, removal and replacement of infected products may be most practical. Portable objects can be fumigated in a vault or plastic bag.

Cerambycidae.[13]—Larvae of the **flat powder-post beetle** *(Smodicum cucijiforme* (Say)) excavate extensive meandering galleries in dry heartwood of oak and hickory. Stored lumber is frequently infested, the larvae continuing to feed until the wood is thoroughly riddled. The adult is 7 to 10 mm long, elongate, very flat, dull yellowish, and shiny. Adults, appearing in July and August, lay eggs in crevices of wood. The larvae excavate tunnels about 3 mm in diameter, tightly packing them with frass, and pupate in an enlarged portion near the surface. There is normally one generation per year, but in dry wood several years may be required to complete the life cycle.

Lyctidae.—These **powder post beetles** cause significant damage to hardwoods. The insects most frequently infesting hardwood flooring and furniture, they are especially common in newly made rustic furniture. Often the wood shows no evidence of insect damage until little mounds of frass begin to appear on rough surfaces, on the floor, or in bureau or buffet drawers. Lyctus larvae are seldom found in unseasoned wood (moisture content over 40 percent, ovendry basis) or in wood dried below 8-percent moisture content. Furthermore, they do not tend to attack old wood as do *Anobiid* beetles. They are often found in sapwood of stored lumber, newly placed oak floors, millwork, in stored merchandise such as hickory or ash tool handles or sporting goods, and in furniture made from infested lumber (Hatfield 1949).

Hardwoods attacked must contain a minimum of 3-percent starch and must have vessels or pores large enough for the female to lay her eggs in them (Gerberg 1957; Hatfield 1958). Thus, the ashes, hickories, and oaks are most seriously damaged; other pine-site hardwoods attacked include elm and sweetgum.

The **southern lyctus beetle**[14] (*Lyctus planicollis* LeC.) is the most common of the destructive powder-post beetles and is particularly injurious in the Southern States. Adults are usually black or almost black and are from 4 to 6 mm long (fig. 11-34). Eggs are laid in open wood pores to depths of 4 to 7.5 mm and hatch within a week or two. The larvae burrow meandering tunnels through the wood and fill them with fine powdery dust. Full-grown larvae are yellowish-white and 3 to 5 mm long. Usually there is one generation per year but occasionally the life cycle may be completed in 4 months or less. Emergence and egg laying are usually heaviest during late winter or early spring. Winter is spent in the larval stage.

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[13] Text under this heading is taken from Baker (1972).

[14] This description is from Baker (1972) based on data from Christian (1940-41) and Wright (1960).

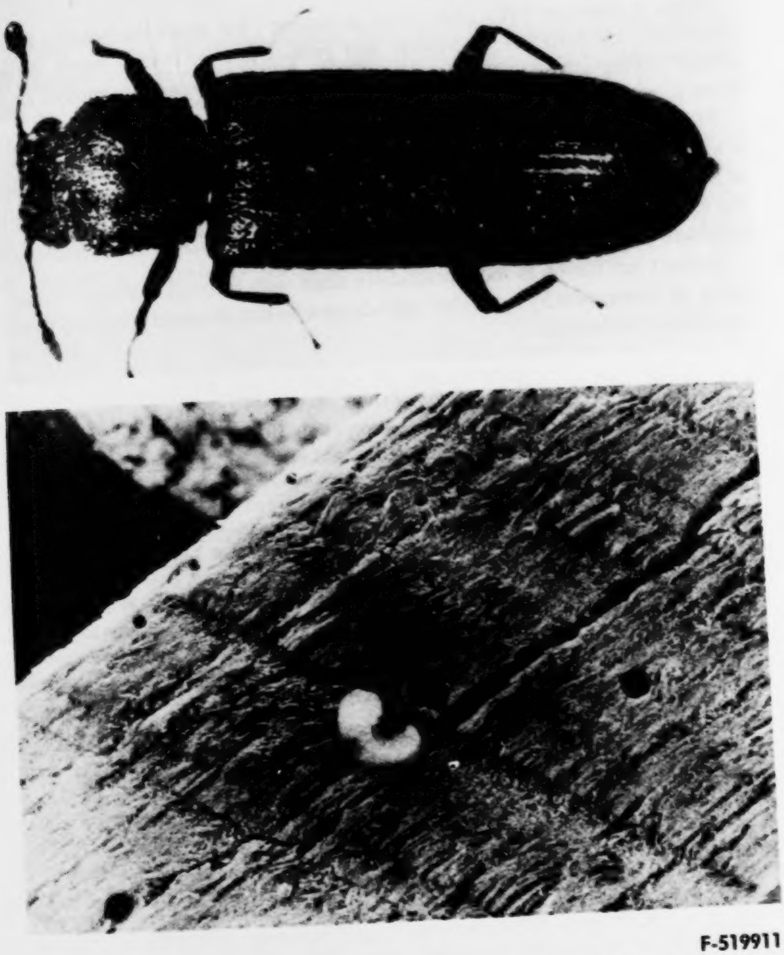

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Figure 11-34.—(Top) Adult southern lyctus beetle measuring about 5 mm long. (Photo from Baker 1972.) (Bottom) Holes made by lyctid beetle in ash furniture (the small holes were made by braconid wasp parasites). The lyctid larva measures about 4 mm long, the beetle about 5 mm. (Photo from files of L. H. Williams, U.S. Dep. Agric. For. Serv.)

CONTROL OF LYCTUS POWDER-POST BEETLES

Dipping green lumber as described in section 11-9 under the heading PROTECTION OF GREEN LUMBER will protect it from lyctus beetle during normal drying storage. These are surface treatments, however; another treatment is needed after it is dry and planed.

Proper kiln-drying of lumber will kill all stages of Lyctus within the wood, *but it will not prevent re-infestation*. Dry lumber also can be purposely heat-treated to kill infestations; the exposure time will vary with thickness of the lumber and the temperature and relative humidity of the kiln. Table 11-8 gives examples of exposure periods necessary to kill the insects.

Product infestation is most practically dealt with through removal, replacement, or fumigation by a certified applicator who has obtained approved from a recognized authority.

TABLE 11-7.—*Kiln schedules for killing Lyctus powder-post beetles in three thicknesses of wood* (Johnston et al. 1955)

Relative humidity, kiln temperature, and thickness of timber (inches)	Exposure period required to kill Lyctus[1]
	Hours
100 percent at 130°F	
1	2.5
2	4.0
3	6.5
80 percent at 120°F	
1	8.0
2	9.5
3	12.0
60 percent at 120°F	
1	9.5
2	11.0
3	13.5
60 percent at 115°F	
1	45.5
2	47.0
3	49.5

[1] After the kiln has reached desired conditions of humidity and temperature.

11-10 MARINE BORERS

Because pine-site hardwoods seldom have straight boles of sufficient length and diameter for salt-water piling, protection of these species against damage from marine borers does not have the economic significance that it has for southern pine.

Pages 713-720 of Agriculture Handbook 420 (Koch 1972) describe the biology and life cycles of the principal marine borers, and will not be repeated here. Chapter 21 of this text discusses preservative treatments of pine-site hardwoods appropriate for all classes of exposure. Of the preservatives listed in table 21-9, only creosote is suitable for hardwoods in marine (salt water) use.

11-11 LITERATURE CITED

Abrahamson, L. P. and F. I. McCracken. 1971. Insect and disease pests of southern hardwoods. *In* Proc. of Symp. on Southeast. Hardwoods, pp. 80-89. Southeast. Area, State and Private For., For. Serv., U.S. Dep. of Agric.

Amburgey, T. L. 1974. Organisms causing discoloration and deterioration of asphalt roofing shingles. For. Prod. J. 24(6):52-54.

Amburgey, T. L. 1978. Preventing discoloration of asphalt roofing shingles and fiberglass panels. For. Prod. J. 28(9):53-55.

American Society for Testing and Materials. 1972. Standard method of accelerated laboratory test of natural decay resistance of woods. ASTM D 2017-71. *In* Annual Book of ASTM Standards, Part 16: 636-642. Philadelphia, Pa.

Applefield, M. 1964. Polyethylene and kraft paper wrappings for protecting kiln-dried lumber stored in the open. Hardwood Res. Counc. Rep. 12. Statesville, N. C. 5 p.

Arnett, R. H. 1963. The beetles of the United States: a manual for identification. 1112 p. Washington, D. C.: Catholic Univ. Amer. Press.

Back, E., and O. T. Carlson. 1955. Composition of resin in chips and chipping sawdust from *Picea excelsa* pulpwood. Svensk Papperstidn. 58:415-420.

Baker, W. L. 1972. Eastern forest insects. U.S. Dep. Agric. For. Serv., Misc. Publ. No. 1175. 642 p. Washington, D. C.

Banfield, W. M. 1968. Dutch elm disease recurrence and recovery in American elm. Mass. Agric. Exp. Stn. Bull. 568, Amherst, Mass. 60 p.

Barger, J. H. and W. K. Hock. 1971. Distribution of Dutch elm disease and the smaller European elm bark beetle in the United States as of 1970. Plant Dis. Rep. 55(3):271-272.

Becker, G. 1972. Protection of wood particle board against termites. Wood Sci. and Technol. 6:239-248.

Behr, E. A. 1972. Decay and termite resistance of medium-density fiberboards made from wood residue. For. Prod. J. 22(12):48-51.

Behr, E. A., and B. A. Wittrup. 1969. (Decay and termite resistance of two species particleboards.) Holzforschung 32:166-170.

Bergman, O. 1973. Wood substance losses in some chip storage experiments. *In* Protection of wood in storage IUFRO Symp. Roy. Coll. For., Dept. For. Prod., Res. Notes R 83, p. XVII 1-28, Stockholm.

Bergman, O. 1974. Thermal degradation and spontaneous ignition in outdoor chip storage. Roy. Coll. For., Dept. For. Prod., Res. Notes R 91, Stockholm, 18 p.

Bergman, O., and T. Nilsson. 1971. (Report on outdoor storage of aspenwood chips at the Hornefors Sulfite Mill.) Institutionen fo Virkeslara, Skogshogskolan. Rapporter R-55:1-60.

Berry, F. H. and J. A. Beaton. 1971. Decay not serious in northern red oak. U.S. Dep. Agric. For. Serv., Res. Note NE-125. 5 p.

Berry, F. H. and J. A. Beaton. 1972. Decay causes little loss in hickory. U.S. Dep. Agric. For. Serv., Res. Note. NE-152. 4 p.

Berry, F. H., and F. F. Lombark. 1978. Basidiomycetes associated with decay of living oak trees. U.S. Dep. Agric. For. Serv. Res. Pap. NE-413. 8 p.

Blew, J. O. 1966. Performance of treated oak crossties. Crosstie Bull. 47(3):7-10, 12-18, 20.

Boggan, J. A. 1977. How Mead Papers learned to use wholetree chips for bleached pulp. Pulp Pap. 51(14):110-113.

Bois, P. J., R. A. Flick, and W. D. Gilmer. 1962. A study of outside storage of hardwood pulp chips in the Southeast. Tappi 45: 609-618.

Boyce, J. S. 1961. Forest pathology. 3rd ed. New York: McGraw Hill. 572 p.

Bravery, A. F. 1971. The application of scanning electron microscopy in the study of timber decay. J. Inst. Wood Sci. 5(6):13-19.

Bravery, A. F., N. Parameswaran, and W. Liese. 1974. [Electron microscopic investigations on the effect of tri-n-butyl tin oxide on the decay of beechwood by *Polystictus versicolor*. Part 1. Observations on solvent-treated control material.] Material und Organismen 9(2):133-144.

Bryan, W. C. 1961. How good are the Piedmont hardwoods? For. Farmer 20(9):8-9.

Burkhardt, E. C. and F. C. Wagner, Jr. 1978. End treatment of hackberry logs to prevent blue stain. For. Prod. J. 28(1):36-38.

Burns, D. P. 1970. Insect enemies of yellow-poplar. U.S. Dep. Agric. For. Serv., Res. Pap. NE-159. 15 p.

Burns, D. 1971a. Yellow-poplar weevil. U.S. Dep. Agric. For. Serv., Leafl. 125. 5 p. Washington, D. C.

Burns, D. P. 1971b. Insects that hurt the bourbon stave industry. The Wooden Barrel 38(6):6-9.

Burns, P. Y. 1955. Fire scars and decay in Missouri oaks. Agric. Exp. Stn. Bull. 642, 8 p. Univ. of Missouri, Columbia, Missouri.

Burns, P. Y., D. M. Christisen, and J. M. Nichols. 1954. Acorn production in the Missouri Ozarks. Bull. No. 611. Univ. Mo. Agric. Exp. Stn., Columbia. 8 p.

Buro, A. 1954. Untersuchungen über den Abbau von Kiefern- und Buchenholz durch holzzerstörende Pilze und deren Einfluss auf einige physikalische Eigenschaften des Holzes. Holz als Roh- und Werkstoff 12:258-267.

Bush, D. L. 1973. A comparison of *Cephalosporium* isolates that cause hardwood wilts. M.S. thesis, Texas A&M Univ., University Station.

Butcher, J. A. 1973. Laboratory screening trials for new prophylactic chemicals against sapstain and decay in sawn timber. Material und Organismen 8:51-70.

Campbell, R. N. 1959. Fungus sap stains of hardwoods. South. Lumberman 199(2489): 115-120.

Campbell, W. A. and A. F. Verrall. 1956. Fungus enemies of hickory. U.S. Dep. Agric. For. Serv., Hickory Task Force Rep. No. 3. 8 p. Southeast. For. Exp. Stn., Asheville, N. C.

Cappellini, R. A., F. N. Matthee, G. H. DeSwardt, J. Beereboom, and L. Ginsburg. 1968. Control of gray-mold of Barlinka grapes during storage and transit. Plant Dis. Rep. 52:479-482.

Cappellini, R. A., and J. L. Peterson. 1969. An experimental broad-spectrum, vapor-phase fungitoxicant. Phytopathology 59:712-713.

Carpenter, B. E., Jr., and E. R. Toole. 1963. Sprinkling with water protects hardwood logs in storage. South. Lumberman 207(2576):25-26.

Carter, F. L., T. L. Amburgey, and F. G. Manwiller. 1976. Resistance of 22 southern hardwoods to wood-decay fungi and subterranean termites. Wood Sci. 8:223-226.

Cartwright, K. St. G., W. G. Campbell, and F. H. Armstrong. 1936. The influence of fungal decay on the properties of timber. I—The effect of progressive decay by *Polyporus hispidus*, Fr., on the strength of English ash (*Fraxinus excelsior* L.). *In* Proc. Ser. B., Roy. Soc., London 120: 76-95.

Cartwright, K. St. G., and W. P. K. Findlay. 1958. Decay of timber and its prevention. Dept. Sci. and Ind. Res., For. Prod. Res. Lab., London: H.M.S.O. Second ed. 332 p.

Cassens, D. L., and W. E. Eslyn. 1981. Fungicides to prevent sapstain and mold on hardwood lumber. For. Prod. J. 31(9): 39-42.

Chidester, M. S. 1939. Further studies on temperatures necessary to kill fungi in wood. *In* Proc., Am. Wood. Preserv. Assoc. 35:319-324.

Christian, M. B. 1940-41. Biology of the powder-post beetles, *Lyctus planicollis* Leconte and *Lyctus Parallelopipedus* (Melsh.). Part I. La. Conserv. Rev. 9(4):56-59. Part II. 10(1):40-42.

Church, T. W., Jr. 1971. Technical considerations in harvesting and sawing defective hardwood butts. U.S. Dep. Agric. For. Serv., Res. Pap. NE-189. 17 p.

Clayton, C. N. 1953. Root rots in the East. *In* Plant Diseases: The Yearbook of Agriculture, p. 711-713. U.S. Dep. Agric., Washington, D. C.

Cockcroft, R., and J. F. Levey. 1973. Bibliography on the use of boron compound in the preservation of wood. J. Inst. Wood Sci. 6(3):28-37.

Cole, H. 1972. Chip pile fire. Pulp and Pap. Mag. Can. 73 (convention issue):137-140.

Cosenza, B. J., M. McCreary, J. D. Buck, and A. L. Shigo. 1970. Bacteria associated with discolored and decayed tissues in beech, birch, and maple. Phytopathology 60:1547-1551.

Coursey, D. G., and R. H. Booth. 1972. The post-harvest phytopathology of perishable tropical produce. Rev. Plant Pathol. 51:751-765.

Cowling, E. B. 1961. Comparative biochemistry of the decay of sweetgum sapwood by white-rot and brown-rot fungi. U.S. Dep. Agric. For. Serv., Tech. Bull. No. 1258. 79 p. Washington, D. C.

Cowling, E. B. and I. B. Sachs. 1960. Detection of brown rot with osmium tetroxide stain. For. Prod. J. 10:594-596.

Crandall, B. S., and W. L. Baker. 1950. The wilt disease of American persimmon, caused by *Cephalosporium diospyri*. Phytopathology 40:307-325.

Dale, F. A. 1976. Preservation of round eucalypt poles in Australia. *In* The performance of treated wood and untreated durable species. Swedish Wood Pres. Inst., No. 124, Stockholm. p. 23-28.

Davidson, R. W, W. A. Campbell, and D. B. Vaughn. 1942. Fungi causing decay of living oaks in the eastern United States and their cultural identification. Tech. Bull. 785, U.S. Dep. Agric., Washington, D. C. 65 p.

DeGroot, R. C., and W. E. Eslyn. 1978. Save wood—end-treat stored maple and birch logs. U.S. Dep. Agric., For. Serv., For. Prod. Lab., Madison, Wis. 6 p.

DeGroot, R. C. and F. I. McCracken. 1977. Micro-organisms affecting quality of hardwood trees growing on southern pine sites and of products made from them. For. Prod. J. 27(6):17-24.

Desai, R. L., and J. K. Shields. 1971. Effect of near ultraviolet light on fungi colonizing hardwood chips. Int. Biodetn. Bull. 7(1):11-13.

Diller J. D. and E. J. Koch. 1959. Weight losses of 40 wood species exposed to *Poria incrassata* and *Merulius lacrymans*. For. Prod. J. 9(9):298-302.

Djerf, A. C., and D. A. Volkman. 1969. Experiences with water spray wood storage. Tappi 52:1861-1864.

Donley, D. E. 1971. Track the hicktory nut weevil. Ohio Woodlands 9(4):13.

Donley, D. E. 1974. Wood borer losses in Appalachian oak. South. Lumberman 229(2848):115-116, 118.

Donley, D. E., C. J. Hay, and D. P. Burns. 1969. Borers in Ohio oaks. Ohio Woodlands 7(4):17-18.

Donley, D. E. and J. R. Terry. 1977. How to identify damage by major oak borers in the eastern United States. U.S. Dep. Agric. For. Serv., Leafl., Northeast. For. Exp. Stn., Upper Darby, Pa.

Donley, D. E., and D. P. Worley. 1976. Insect impact on production of oak timber. South. Lumberman 233(2895):63-66.

Downs, A. A. and W. E. McQuilkin. 1944. Seed production of southern Appalachian oaks. J. of For. 42:913-920.

Duncan, C. G. 1960. Deterioration of wood by terrestrial ascomycetes and fungi imperfecti. *In* Developments in industrial microbiology, Vol. 1. p. 148-156. Plenum Press.

Duncan, C. G. 1961. Relative aeration requirements by soft rot and basidiomycete wood-destroying fungi. U.S. Dep. Agric. For. Serv. For. Prod. Lab., Madison, Wis. Rpt. No. 2218. 6 p.

Duncan, C. G. 1965. Determining resistance to soft-rot fungi. U.S. Dep. Agric. For. Serv. Res. Pap. FPL 48. 12 p.

Ebel, B. H. 1967. Piedmont hardwoods—Which do wood borers damage? South. Lumberman 215(2680): 113-114.

Eckert, J. W., and N. F. Sommer. 1967. Control of diseases of fruits and vegetables by postharvest treatment. *In* Horsfall, J. G., and K. F. Baker (eds.,) Annual Review of Phytopathology 5:391-432. Annual Reviews, Inc., Palo Alto, Calif.

Englerth, G. H. 1946. Deterioration of fiberboard by molds. For. Pathol. Spec. Rel. 29. U.S. Dep. Agric., For. Prod. Lab., Madison, Wis. 7 p.

Englerth, G. H. 1950. Decay resistance of plywood bonded with various glues. For. Prod. Res. Soc. Proc. 4:248-253.

Eriksson, K. -E., B. Pettersson, and U. Westermark. 1975. Enzymic mechanisms of cellulose degradation caused by the rot fungus *Sporotrichum pulverulentum*. *In* Biological Transformation of Wood by Microorganisms (W. Liese, ed.), p. 143-152. Springer-Verlag, New York.

Eriksson, K-E., B. Pettersson, and U. Westermark. 1974. Oxidation: An important enzyme reaction in fungal degradation of cellulose. F.E.B.S. Letters 49(2):282-285.

Eslyn, W. E. 1967. Outside storage of hardwood chips in the northeast. II. Microbiological effects. Tappi 50:297-303.

Eslyn, W. E. 1973a. Evaluating chemicals for controlling biodeterioration of stored wood chips. For. Prod. J. 23(11):21-25.

Eslyn, W. E. 1973b. Propionic acid—a potential control for deterioration of wood chips stored in outside piles. Tappi 56(4):152-153.

Eslyn, W. E. and R. W. Davidson. 1976. Some wood-staining fungi from pulpwood chips. Mem. of the N. Y. Bot. Garden (28(1):50-57.

Eslyn, W. E. and T. L. Highley. 1976. Decay resistance and susceptibility of sapwood of fifteen tree species. Phytopathol. 66:1010-1017.

Eslyn, W. E., T. K. Kirk, and M. J. Effland. 1975. Changes in the chemical composition of wood caused by six soft-rot fungi. Phytopathol. 65:473-476.

Eslyn, W. E. and J. F. Laundrie. 1975. Effect of anaerobic storage upon quality of aspen pulpwood chips. Tappi 58(6):109-110.

Feist, W. C., E. L. Springer, and G. J. Hajny. 1971. Encasing wood chip piles in plastic membranes to control chip deterioration. Tappi 54:1140-1142.

Feist, W. C., G. J. Hajny, and E. L. Springer. 1973. Effect of storing green wood chips at elevated temperatures. Tappi 56(8):91-95.

Feist, W. C., E. L. Springer, and G. J. Hajny. 1973. Spontaneous heating in piled wood chips—contribution of bacteria. Tappi 56(4):148-151.

Ference, G. M. and T. L. Gilles. 1956. The deterioration of straw-piled pulpwood. Tappi 39:406-415.

Filer, T. H., Jr. 1973. Suppression of elm phloem necrosis symptoms with tetracycline antibiotics. Plant Dis. Rep. 57:341-343.

Filer, T. H., Jr., and F. I. McCracken. 1969. *Clitocybe tabescens* associated with decline and death of Chinese elm and water oak. Plant Dis. Rep. 53:840.

Filer, T. H., J. D. Solomon, F. I. McCracken, F. L. Oliveria, R. Lewis, Jr., M. J. Weiss, and T. J. Rogers. 1977. Sycamore pests: a guide to major insects, diseases, and air pollution. 36 p. Southeast. Area, S&PF, Atlanta, Ga. and South. For. Exp. Stn., New Orleans, La.

Findlay, W. P. K., and J. G. Savory. 1950. Breakdown of timber in water-cooling towers. Int. Bot. Congr. Proc. 7:315-316.

Findlay, W. P. K., and J. G. Savory. 1954. Moderfäule. Die Zersetzung von Holz durch niedere Pilze. Holz als Roh- und Werkstoff 12:293-296.

French, D. W. and C. M. Christensen. 1969. Coated insulating board: influence of coating additives and relative humidity upon spotting by fungi. For. Prod. J. 19(9):108-110.

Garren, K. H. 1949. Leader dieback—a "new" disease of sweetgum. Plant Dis. Rep. 33:351-353.

Gerberg, E. J. 1957. Lyctid powder post beetle second only to termite in wood damage. Pest Control 25(5):37, 38, 40.

Gibson, L. P. 1972. Insects that damage white oak acorns. U.S. Dep. Agric. For. Serv., Res. Pap. NE-220. 7 p.

Gjovik, L. R., and H. L. Davidson. 1975. Service records on treated and untreated fenceposts. U.S. Dep. Agric. For. Serv. FPL-068. 45 p.

Grano, C. X. 1957. Pruning-wound closure on southern red oak. J. For. 55:669.

Great Britain Department of Science and Industry. 1950. Effect of fungal decay on the strength of wood. For. Prod. Res. Bd. Rpt. 1939-1947:27.

Greaves, H. 1971. The effect of substrate availability on cellulolytic enzyme production by selected wood-rotting microorganisms. Aust. J. Biol. Sci. 24:1169-1180.

Greaves, H., and J. E. Levy. 1965. Comparative degradation of the sapwood of Scots pine, beech, and birch by *Gleophyllum traveum*, *Polystictus versicolor*, *Chaetomium globosum*, and *Bacillus polymyxa*. J. Inst. Wood Sci. 15:55-63.

Gruschow, G. F. and K. B. Trousdell. 1959. Incidence of rot in hardwood sawtimber in coastal North Carolina. J. For. 57:370-371.

Hardin, K. I., and K. E. Evans. 1976. Cavity nesting bird habitat in the oak-hickory forest—A review. U.S. Dep. Agric. For. Serv. Tech. Rep. NC-30. 23 p.

Harmsen, L., and T. V. Nissen. 1966. Bacterial attacks on wood. U.S. Dep. Agric. For. Serv., FPL-657. (Trans. from German, Holz als Roh- und Werkstoff 23:389-393, by Joint Pub. Res. Serv., Dept. Commer.) 11 p.

Hatfield, I. 1949. Wood boring beetles that damage furniture and interior woodwork. For. Prod. Res. Soc. Proc. 3:235-248.

Hatfield, I. 1958. Wood-destroying organisms: Part two. Diagnosing causes of wood deterioration. Pest Control 26(4):50, 52-54, 56-58, 60.

Hatton, J. V., ed. 1979. Chip quality monograph. Pulp and Paper Technology Series No. 5, Tech. Assoc. Pulp Pap. Ind., Atlanta, Ga.

Hay, C. J. 1972. Woodpecker predation on red oak borer in black, scarlet, and northern red oak. Ann. of the Entomol. Soc. of Amer. 65 :1421-1423.

Hay, C. J. and R. C. Morris. 1961. Carptenterworm. U.S. Dep. Agric. For. Serv., For. Pest Leafl. 64. 8 p. Washington, D. C.

Hay, C. J. and J. F. Wootten, 1955. Insect damage in hardwood sawlogs. U.S. Dep. Agric. For. Serv., Tech. Pap. No. 148. 15 p. Cent. States For. Exp. Stn., Columbus, Ohio.

Hedlund, A. 1959. Look at the scars! South. Lumberman 199(2489):225-226.

Heinrich, H. J., and B. Kaesche-Krischer. 1962. Beitrag zur Aufklarung der Selbstentzundung von Holz. Brennstoff-Chemie 43(5):142-148.

Hepting, G. H. 1935. Decay following fire in young Mississippi delta hardwoods. U.S. Dep. Agric. For. Serv., Tech. Bull. 494. 32 p. Washington, D. C.

Hepting, G. H. 1941. Prediction of cull following fire in Appalachian oaks. J. Agric. Res. 62(2):109-120.

Hepting, G. H. 1955. The current status of oak wilt in the United States. For. Sci. 1:95-103.

Hepting, G. H. 1971. Diseases of forest and shade trees of the United States. U.S. Dep. Agric., Agric. Handb. 386, 658 p.

Hepting, G. H., K. H. Garren, and P. W. Warlick. 1940. External features correlated with top rot in Appalachan oaks. J. For. 38:873-876.

Hepting, G. H. and G. G. Hedgcock. 1935a. Relation between butt rot and fire in some eastern hardwoods. U.S. Dep. Agric. For. Serv., Tech. Note No. 14, 2 p. Appalachian For. Exp. Stn.

Hepting, G. H. and G. G. Hedgcock. 1935b. Relation of cull percent to tree diameter and to percentage of trees with basal wounds in some eastern hardwoods. U.S. Dep. Agric. For. Serv., Tech. Note 16. 4 p. Appalachian For. Exp. Stn.

Hepting, G. H., and J. W. Kimmey. 1949. Heart rot. *In* Trees: the Yearbook of Agriculture, p. 462-465. U.S. Dep. Agric., Washington, D. C.

Highley, T. L., and T. K. Kirk. 1979. Mechanisms of wood decay and the unique features of heartrots. Phytopathology 69:1151-1157.

Highley, T. L. and J. F. Lutz. 1970. Bacterial attack in water-stored bolts. For. Prod. J. 20(4):43-44.

Highley, T. L., T. C. Scheffer, and M. L. Selbo. 1971. Wood minesweepers are sound after 15 years of service. For. Prod. J. 21(5): 46-48.

Hulme, M. A. and D. W. Stranks. 1976. Heat tolerances of fungi inhabiting chip piles. Wood Sci. 8:237-241.

Johnston, H. R. 1952. Practical methods for the control of insects attacking green logs and lumber. J. of the For. Prod. Res. Soc. 2(3):79-84.

Johnston, H. R., R. H. Smith, and R. A. St. George. 1955. Prevention and control of Lyctus powder-post beetles. South. Lumberman 190(2375):72, 74.

Jones, T. W., and W. R. Phelps. 1972. Oak wilt. U.S. Dep. Agric. For. Serv., For. Pest Leafl. 29, 7 p.

Jutte, S. M. and R. A. Zabel. 1974. Initial wood decay stages as revealed by scanning electron microscopy. *In* Scanning electron microscopy 1974 (Part II) Proc. of the Workshop on scanning electron microscope and the plant sci., pp. 445-452. Chicago, Ill.: IIT Res. Inst.

Kandeel, S. A., and E. A. McGinnes, Jr. 1970. Ultrastructure of ring shake in scarlet oak (*Quercus coccinea* Muench.). Wood Sci. 2 :171-178.

Kennedy, R. W. 1958. Strength retention in wood decayed to small weight losses. For. Prod. J. 8:308-314.

Kinbara, T., and A. Kawasaki. 1967. (Spontaneous ignition of wooden materials heated for a long time at a low temperature.) Bull. Fire Prev. Soc. of Japan 16(2):9-16. Transl. by Can. Dep. Fish. and For., 1971, Ottawa.

Kirk, T. K. 1973. The chemistry and biochemistry of decay. *In* Wood deterioration and its prevention by preservative treatments. Vol. I. (D. D. Nicholas, Ed.) Syracuse Univ. Press, New York.

Kirk, T. K. 1975. Lignin-degrading enzyme system. *In* Biotechnol. and Bioeng. Symp. No. 5:139-150. John Wiley and Sons, Inc.: New York.

Kirk, T. K., and C. H. Kirk. 1978. Wood deterioration. *In* McGraw-Hill 1978 Yearbook of Science and Technology. p. 389-391. McGraw-Hill Book Company, New York.

Koch, P. 1972. Utilization of the southern pines. U.S. Dep. Agric. For. Serv., Agric. Handb. 420. 1663 p. 2 vol. U.S. Govt. Print. Off., Washington, D. C.

Koenigs, J. W. 1974. Hydrogen peroxide and iron: A proposed system for decomposition of wood by brown-rot basidiomycetes. Wood and Fiber 6:66-79.

Kowal, R. J. and B. H. Ebel. 1971. Insects attacking forest trees in the South. For. Farmer Man. 30(7):89-94.

Kramer, P. R. 1954. Results of spraying pine and hardwood logs for control of insects and stain. Tech. Rep. No. 8, 18 p. Tx. For. Serv.

Lentz, G. H. 1929. Loss in merchantable red gum due to two fires. South. Lumberman 135(1756):40.

Lewis, R. L., and E. P. Van Arsdel. 1975. Disease complex in Texas A&M University campus sycamores. (abstr.) *In* Proc., Am. Phytopathol. Soc., Vol. 2, p. 137.

Liese, W. 1970. Ultrastructural aspects of woody tissue disintegration. Ann. Rev. Phytopathology 8:231-258.

Lindgren, R. M. 1942. Temperature, moisture, and penetration studies of wood-staining Ceratostomellae in relation to their control. U.S. Dep. Agric. Tech. Bull. 807. 35 p.

Lindgren, R. M. 1953. Deterioration losses in stored southern pine pulpwood. Tappi 36:260-264.

Lindgren, R. M., and W. E. Eslyn. 1961. Biological deterioration of pulpwood and pulp chips during storage. Tappi 44:419-429.

McCracken, F. I. 1974. Butt rot in southern bottomland hardwoods. (abstr.) *In* Proc., Am. Phytopathol. Soc. Vol. 1, p. 164.

McCracken, F. I. 1977. Butt rot of southern hardwoods. U.S. Dep. Agric., For. Ins. Dis. Leafl. 43, rev. 8 p.

McCracken, F. I., and E. R. Toole. 1974. Felling infected oaks in natural stands reduces dissemination of *Polyporus hispidus* spores. Phytopathology 64:265-266.

McGinnes, E. A., Jr. 1965. Extent of shake in Missouri oaks. For. Prod. J. 15(5):190.

McGinnes, E. A., Jr. 1974. Abnormal wood formations—their causes and effects on wood utilization. *In* Proc., Int. Exhib. for Furniture and Wood-Working Mach. Gen. Organ. for Int. Exhib. and Fairs, Cairo, Egypt.

McGinnes, E. A., Jr., J. E. Phelps, and J. C. Ward. 1974. Ultrastructure observations of tangential shake formations in hardwoods. Wood Sci. 6:206-211.

McGinnes, E. A., Jr., and K. Y-T. Wu. 1973. Intra-incremental chemical studies of ring shake in scarlet oak. Wood Sci. 5:287-294.

McKee, J. C., and J. W. Daniel. 1966. Long term storage of pulpwood in sealed enclosures. Tappi 49(5):47A-50A.

McLean, D. M. 1944. Histo-pathologic changes in the phloem of American elm affected with the virus causing phloem necrosis. Phytopathology 34:818-826.

McQuilkin, W. E. 1950. Effects of some growth regulators and dressings on the healing of tree wounds. J. For. 48:423-428.

Martin, J. S. 1956. Sulfate pulping of logging and sawmill wastes of old-growth Douglas-fir and of certain associated species. Rep. No. R1747, U.S. Dep. Agric. For. Serv., For. Prod. Lab., Madison, Wis. 17 p.

Merrill, W. 1965. Decay of wood and wood fiberboards by common fungi imperfecti. Holz und Org. 1:69-76.

Merrill, W., and D. W. French. 1963. Evaluating preservative treatment of rigid insulating materials. Tappi 46:449-452.

Merrill, W., and R. L. Hossfeld. 1965. Effects of common molds on physical and chemical properties of wood fiberboard. Part II of a series of wood fiberboard studies. Tappi 48:470-474.

Miller, P. R., and G. F. Gravatt. 1952. The sweetgum blight. Plant Dis. Rep. 36:247-252.

Mobley, H. E., and E. Kerr. 1973. Wildfire versus prescribed fire in the southern environment. Southeast. Area, State and Private For., U.S. Dep. Agric. For. Serv., 6 p.

Morris, R. C. 1955. Insect problems in southern hardwood forests. South. Lumberman 19(2393):136-139.

Morris, R. C. 1959. Insects cause degrade in Ozark oaks. U.S. Dep. Agric. For. Serv., South. For. Notes No. 120, p. 2-3. South. For. Exp. Stn., New Orleans, La.

Morris, R. C. 1964. Value losses in southern hardwood lumber from degrade by insects. U.S. Dep. Agric. For. Serv., Res. Pap. SO-8, 6 p.

Morris, R. C. 1965. Controlling insect damage to southern hardwood forests. *In* Insects in southern forests. Proc., fourteenth annu. for. symp., pp. 114-124. La. State Univ., Baton Rouge, La.

Morris, R. C. 1974. Log storage can affect hardwood quality. South. Lumberman 229(2837):19-20.

Morris, R. C. 1977. Insect-caused degrade in hardwood lumber. South. Lumberman 234(2902):19-20.

Nicholls, G. A., L. Lindevall, and G. W. Mitchell. 1974. Chip irradiation, glucomannan retention, and economic prospects for increased kraft pulp yields. Tappi 51(11):91-94

Oliveria, F. L. 1976. Ambrosia beetles, especially *Corthylus columbianus*, and degradation in hardwood trees and lumber. *In* Research on insect borers of hardwoods—current status, needs, and application, proc. of a res. coordination meet., pp. 38-41. For. Insect and Dis. Res., For. Serv., U.S. Dep. of Agric., Washington, D. C.

Peacock, J. W. 1975. Research on chemical and biological controls for elm bark beetles, pp. 18-28. *In* Dutch elm disease, proc. of IUFRO Conf. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Peterson, M. D. 1977. Ultrastructural studies on the mechanism of initial cell wall penetration and lysis by a white rot and a brown rot fungus in ash, yellow-poplar, and loblolly pine. Ph.D. Thesis, Dept. Wood and Pap. Sci., N. C. State Univ., Raleigh.

Reid, V. H. and P. D. Goodrum. 1957. Factors influencing the yield and wildlife use of acorns. *In* Special problems in southern forest management, proc. sixth annu. for. symp., pp. 46-79. Baton Rouge, La.: La. State Univ.

Rexrode, C. O. 1971. Insect damage to oaks. *In* Oak symp. proc., p. 129-134. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Rhoads, A. S. 1950. *Clitocybe* root rot on woody plants in the Southeastern United States. U.S. Dep. Agric. Circ. 583, 25 p.

Rhoads, A. S. 1956. The occurrence and destructiveness of Clitocybe root rot of woody plants in Florida. Lloydia 19:193-240.

Rhyne, J. B., and A. W. Brinkley, Jr. 1961. Seven months outside storage of pine and hardwood chips at the Panama City mill of International Paper Company. South. Pulp and Pap. Manuf. 24(2):86, 88, 116-117.

Richards, D. B. 1954. Physical changes in decaying wood. J. of For. 52: 260-265.

Roff, J. W., A. J. Cserjesi, and G. W. Swann. 1974. Prevention of sap stain and mold in packaged lumber. Dep. Environ., Can. For. Serv. Publ. 1325, 48 p.

Roth, E. R. 1939. The effect of pruning on the heartrot hazard in hardwoods. U.S. Dep. Agric. Bur. Plant Ind., Civilian Conservation Corps. 13 p.

Roth, E. R. 1948. Healing and defects following oak pruning. J. For. 46:500-504.

Roth, E. R. 1950. Cankers and decay of oak associated with *Irpex mollis*. Plant Dis. Rep. 34: 347-348.

Savory, J. G. 1954a. Damage to wood caused by micro-organisms. J. Appl. Bacteriol. (London) 17:213-218.

Savory, J. G. 1954b. Breakdown of timber by Ascomycetes and Fungi Imperfecti. Ann. Appl. Biol. 41: 336-347.

Savory, J. G. 1955. The role of the microfungi in the decomposition of wood. Rec. Brit. Wood Preserve. Assoc. 5:3-19.

Savory, J. G., and L. C. Pinion. 1958. Chemical aspects of decay of beech wood by *Chaetomium globosum*. Holzforschung 12:99-103.

Scheffer, T. C. 1936. Progressive effects of *Polyporous versicolor* on the physical and chemical properties of red gum sapwood. U.S. Dep. Agric., Tech. Bull. No. 527. 46 p. Washington, D. C.

Scheffer, T. C. 1943. The decay resistance of oak wood. U.S. Bur. Plant Ind., Soils, and Agric. Eng., Div. For. Pathol., Spec. Rel. No. 13, 6 p.

Scheffer, T. C. 1964. (Biological observations of significance for improved preservative treatment.) Holzforschung 18:88-94.

Scheffer, T. C. 1969. Protecting stored logs and pulpwood in North America. Material und Organismen 4:167-199.

Scheffer, T. C., and M. S. Chidester. 1948. Survival of decay and bluestain fungi in air-dry wood. South. Lumberman 177 (2225):110-112.

Scheffer, T. C., and E. B. Cowling. 1966. Natural resistance of wood to microbial deterioration. Ann. Rev. Phytopath. 4:147-170.

Scheffer, T. C., G. H. Englerth, and C. G. Duncan. 1949. Decay resistance of seven native oaks. J. of Agric. Res. 78(5, 6):129-152.

Scheffer, T. C. and W. E. Eslyn. 1961. Effect of heat on the decay resistance of wood. For. Prod. J. 11:485-490.

Scheffer, T. C., and R. D. Graham. 1972. Paradichlorobenzene for temporary protection of wood against fungi. For. Prod. J. 22(8):40-41.

Scheffer, T. C., and R. M. Lindgren. 1940. Stains of sapwood and sapwood products and their control. U.S. Dep. Agric. Tech. Bull. 714. 124 p.

Schipper, A. L., and D. W. French. 1971. Fungi in insulating board and in air within mills. Int. Biodetn. Bull. 7:125-128.

Schmidt, E. L., D. W. French, R. O. Gertjejansen, J. Hermann, and H. Hall. 1978. Strength reductions in particleboard caused by fungi. For. Prod. J. 28(2):26-31.

Sheridan, T. G. 1958. A mill survey of wood deterioration and its effect on pulp yield and quality. Pulp. Pap. Mag. Can. 59:228-235.

Shigo, A. L. 1965. The pattern of decays and discoloration in northern hardwoods. Phytopathology 55:648-652.

Shigo, A. L. 1966. Decay and discoloration following logging wounds on northern hardwoods. U.S. Dep. Agric. For. Serv. Res. Pap. NE-47.

Shigo, A. L. 1967. Successions of organisms in discoloration and decay of wood. *In* Int. Rev. For. Res. Vol. 2, p. 237-299. Academic Press, New York.

Shigo, A. L. 1972a. Ring and ray shakes associated with wounds in trees. Holzforschung 26:60-62.

Shigo, A. L. 1972b. Successions of microorganisms and patterns of discoloration and decay after wounding in red oak and white oak. Phytopathology 62:256-259.

Shigo, A. L. 1979. Tree decay. An expanded concept. Agric. Inf. Bull. No. 419, U.S. Dep. Agric. For. Serv. 73 p.

Shigo, A. L., and E. vH. Larson. 1969. A photo guide to the patterns of discoloration and decay in living northern hardwood trees. U.S. Dep. Agric. For. Serv. Res. Pap. NE-127. Northeast. For. Exp. Stn., Upper Darby, Pa.

Shigo, A. L., and A. Shigo. 1974. Detection of discoloration and decay in living trees and utility poles. U.S. Dep. Agric. For. Serv., Res. Pap. NE-294, 11 p.

Shigo, A. L., J. Stankewich, and B. J. Cosenza. 1971. *Clostridium* sp. associated with discolored tissues in living oaks. Phytopathol. 61:122-123.

Shigo, A. L. and C. L. Wilson. 1972. Discoloration associated with wounds one year after application of wound dressings. Arborist's News 37(11):121-132.

Siegle, H. 1967. Microbiological and biochemical aspects of heartwood stain in *Betula papyrifera* Marsh. Can. J. Bot. 45:147-154.

Silverbog, S. B. 1954. Northern hardwoods cull manual. State Univ. of New York. Coll. of For. at Syracuse. Bull. 31, 45 p.

Smith, R. S. 1975. Economic aspects of bacteria in wood. *In* Biological transformation of wood by microorganisms. Proc., Sessions on Wood Prod. Pathology at the Sec. International Congr. of Plant Pathology, Sept. 10-12, Minneapolis. (W. Liese, ed.) Berlin: Springer-Verlag. p. 89-102.

Smith, R. S., and L. R. Gjovik. 1972. Interlaboratory testing of wood preservatives using ASTM D1413-61. Wood and Fiber 4:170-178.

Smith, R. S. and J. V. Hatton. 1971. Economic feasibility of chemical protection for outside chip storage. Tappi 54:1638-1640.

Smith, V. K. 1968. Lindane controls *Lyctus* powder-post beetles during air-drying of rough ash lumber. J. Econ. Ecol. 61:323-324.

Snyder, T. E. 1941. Control of ambrosia beetles. South. For. Notes 39. 2 p.

Solomon, J. D. 1969. Woodpecker predation on insect borers in living hardwoods. Ann. of the Entomol. Soc. of Am. 62:1214-1215.

Solomon, J. D. 1972. Biology and habits of the living beech borer in red oaks. J. of Econ. Entomol. 65(5):1307-1310.

Solomon, J. D. 1974. Biology and damage of the hickory borer, *Goes pulcher*, in hickory and pecan. Ann. of the Entomol. Soc. of Am. 67(2):257-260.

Solomon, J. D. 1975. Biology of an ash borer, *Podesesia syringae*, in green ash in Mississippi. Ann. of the Entomol. Soc. of Am. 68(2): 325-328.

Solomon, J. D. 1976. Sap beetle involvement in the formation of sap spots on oaks in Mississippi. J. Ga. Entomol. Soc. 11(1):17-27.

Solomon, J. D. 1977a. Impact and control of insect borers in southern hardwoods. *In* Proc. of the second symp. on southeastern hardwoods, p. 94-100. U.S. Dep. Agric. For. Serv., Southeast. Area State and Private For, Atlanta, Ga.

Solomon, J. D. 1977b. Biology and habits of the oak branch borer (*Goes debilis*). Ann. Entomol. Soc. of Am. 70(1):57-59.

Solomon, J. D. 1977c. Frass characteristics for identifying insect borers (*Lepidoptera: Cossidae* and *sesidae: Coleoptera: Cerambycidae*) in living hardwoods. Can. Ent. 109:295-303.

Solomon, J. D., and M. E. Dix. 1979. Selected bibliography of the clearwing borers (Sesiidae) of the United States and Canada. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. SO-22. 18 p.

Solomon, J. D. and C. J. Hay. 1974. Annotated bibliography of the carpenterworm, *Prionoxystus robiniae*. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. SO-4. 13 p.

Solomon, J. D., F. I. McCracken, R. L. Anderson, R. Lewis, Jr., F. L. Oliveria, T. H. Filer, and P. J. Barry. 1980. Oak pests. A guide to major insects, diseases, air pollution, and chemical injury. U.S. Dep. Agric. For. Serv., Gen. Rep. SA-GR11. 69 p.

Solomon, J. D. and R. C. Morris 1965. White oak borer major hardwood pest in Mississippi. Miss. Farm Res. 28(11):4.

Solomon, J. D. and R. C. Morris. 1966. Clearwing borer in red oaks. U.S. Dep. Agric. For. Serv., Res. Note SO-39. 3 p.

Solomon, J. D. and R. C. Morris. 1971. Woodpeckers in the ecology of southern hardwood borers. *In* Proc., second tall timbers conf. on ecol. animal control by habitat manage., pp. 309-315.

Solomon, J. D. and E. R. Toole. 1971. Stain and decay around carpenterworm galleries in southern hardwood trees. U.S. Dep. Agric. For. Serv., Res. Note SO-120. 4 p.

Solomon, J. D., T. E. Vowell, Jr., and R. C. Horton. 1975. Hackberry butterfly, *Asterocampa celtis*, defoliates sugarberry in Mississippi. J. Ga. Entomol. Soc. 10(1):17-18.

Southern Pulp and Paper Manufacturer. 1977. Virginia-Carolina discusses chip handling and coating operations at Richmond meeting. South. Pulp Pap. Manuf. 40(2):56, 58.

Springer, E. L., W. E. Eslyn, L. L. Zoch, Jr., and G. J. Hajny. 1969. Control of pulp chip deterioration with kraft green liquor. U.S. Dep. Agric. For. Serv. Res. Pap. FPL-110, 4 p. For. Prod. Lab., Madison, Wis.

Springer, E. L., E. J. Haslerud, D. M. Fries, I. T. Clark, G. J. Hajny, and L. L. Zoch, Jr. 1971. An evaluation of four chemicals for preserving wood chips stored outdoors. Tappi 54:555-560.

Springer, E. L., L. L. Zoch, Jr., W. C. Feist, and G. J. Hajny. 1973. A treatment that shows promise for preserving stored wood chips. U.S. Dep. Agric. For. Serv., Res. Pap. FPL 216. 4 p.

Springer, E. L., L. L. Zoch, Jr., W. C. Feist, C. J. Hajny, and R. W. Hemingway. 1978. Storage characteristics of southern pine whole-tree chips. *In* Complete tree utilization of southern pine: symposium proceedings, New Orleans, April 17-19, C. W. McMillin, ed., p. 216-223. For, Prod. Res. Soc.

Stewart, E. L., M. E. Palm, J. G. Palmer, and W. E. Eslyn. 1979. Deuteromyetes and selected Ascomycetes that occur on or in wood: An indexed bibliography. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. FPL 24. 165 p.

Stolley, I. 1958. Some methods for treating particle boards to increase their resistance to fungi and termites. Proc. Intern. Consultation on Insulating Boards, Hardboards, and Particleboard, Geneva, 1957. Pap. 5. 38. UNFAO, Rome. 6 p.

Swingle, R. V., R. R. Whitten, and H. C. Young. 1949. The identification and control of elm phloem necrosis and Dutch elm disease. Ohio Agric. Exp. Stn., Spec. Circ. 80, 11 p.

Toole, E. R. 1955. *Polyporus hispidus* on southern bottomland oaks. Phytopathology 45:177-180.

Toole, E. R. 1959. Decay after fire injury to southern bottom-land hardwoods. U.S. Dep. Agric. For. Serv., Tech. Bull. No. 1189. 25 p. Washington, D. C.

Toole, E. R. 1960a. Butt rot of southern hardwoods. U.S. Dep. Agric. For. Serv. For. Pest Leafl. 43. 4 p.

Toole, E. R. 1960b. Root rot of white oak in Arkansas. Plant Dis. Rep. 44(10):783.

Toole, E. R. 1960c. When to look for hardwood blight. For. and People, 1st Qtr., p. 14, 15, 48.

Toole, E. R. 1965. Deterioration of hardwood logging slash in the South. U.S. Dep. Agric. For. Serv., Tech. Bull. No. 1328. 27 p. Washington, D. C.

Toole, E. R. 1967. Root rot of southern hardwood trees caused by corticium galactinum. Plant Dis. Rep. 51:500-501.

Toole, E. R. 1970. Changes in weight loss and dimensions of wood infected with brown-rot fungi. For. Prod. J. 20(6):51-52.

Toole, E. R. 1971. Reduction in crushing strength and weight associated with decay by rot fungi. Wood Sci. 3:172-178.

Toole, E. R. 1972. Effect of decay fungi on the microstructure of red oak heartwood. Wood Sci. 5:34-37.

Toole, E. R. and H. M. Barnes. 1974. Biodeterioration of particleboard. For. Prod. J. 24(10):55-57.

Toole, E. R. and W. N. Darwin, Jr. 1970. Influence of variation in physical and chemical properties of southern red oak lumber on decay resistance. Miss. State Univ. For. Prod. Util. Lab. Tech. Rep. No. 10. 8 p.

Toole, E. R., and P. C. Lightle. 1960. Status of persimmon wilt, 1959. Plant Dis. Rep. 44:45.

Tryon, E. H., C. B. Koch, and W. C. Percival. 1975. Ring width and rate of decay in oak. Wood Sci. 7:292-294.

U.S. Agricultural Research Service. 1960. Index of plant diseases in the United States. U.S. Dep. Agric., Agric. Handb. 165. 531 p.

U.S. Department of Agriculture, Forest Service. 1963. Continuous water spray ineffective in preventing ambrosia beetle attack in gum logs. U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Annual Rep. 1962:39-40.

U.S. Department of Agriculture, Forest Service. 1967a. Factors influencing decay of untreated wood. U.S. Dep. Agric. For. Serv., Res. Note FPL-0154. 3 p.

U.S. Department of Agriculture, Forest Service. 1967b. Comparative decay resistance of heartwood of native species. U.S. Dep. Agric. For. Serv., Res. Note FPL-0153. 2 p.

U.S. Department of Agriculture, Forest Service. 1974. Wood handbook: Wood as an engineering material. U.S. Dep. Agric. For. Serv., Agric. Handb. 72, rev. For. Prod. Lab., Madison, Wis.

Unligil, H. A. 1976. Prevention of fungal stain on pine lumber—laboratory screening tests with fungicides. For. Prod. J. 26(1):32-33.

Van Arsdel, E. P., and R. S. Halliwell. 1970. Progress in research on live oak decline. Plant Dis. Rep. 54:669-672.

Verrall, A. F. 1945. The control of fungi in lumber during air-seasoning. Bot. Rev. 11:398-415.

Von Schrenk, H., and P. Spaulding. 1909. Diseases of deciduous forest trees. U.S. Bur. Plant Ind. Bull. 149, 84 p.

Wagener, W. W., and R. W. Davidson. 1954. Heart rots in living trees. Botan. Rev. 20(2):61-134.

Wagner, F. G. 1976. Experience with stain, decay, and insects in Mid-South log storage yards. South. Lumberman 232(2874):9-12.

Ward, J. C., R. A. Hann, R. C. Baltes, and E. H. Bulgrin. 1972. Honeycomb and ring failure in bacterially infected red oak lumber after kiln drying. U.S. Dep. Agric. For. Serv., Res. Pap. FPL 165. 36 p.

Wagner, F. G., Jr., E. C. Burkhardt, and D. Caranna. 1977. Whole-log treatment of hackberry to prevent blue stain. South. Lumberman 235(2920):93-94.

Weiner, J., L. Roth, E. B. Cowling, and W. L. Hafley. 1974. Changes in the value and utility of pulpwood, sawlogs, and veneer bolts during harvesting, transport, and storage. Inst. Pap. Chem. Biblio. Ser. Spec. No. 60, Appleton, Wis. 629 p.

White, L. T. 1951. Studies of Canadian Thelephoraceae. VIII. *Corticium galactinum* (Fr.) Burt. Can. J. Bot. 29:279-296.

White, M. A., and P. A. DeLuca. 1978. Bulk storage effects on the fuel potential of sawmill residues. For. Prod. J. 28(11):24-29.

Wilcox, W. W. 1965. Fundamental characteristics of wood decay. For. Prod. J. 9(7):255-259.

Wilcox, W. W. 1968. Changes in wood microstructure through progressive stages of decay. U.S. Dep. Agric. For. Serv., Res. Pap. FPL 70. 46 p.

Wilcox, W. W. 1973. Degradation in relation to wood structure. *In* Wood deterioration and its prevention by preservative treatments. Vol. I, Degradation and protection of wood. (D. D. Nicholas, ed.), p. 107-148. Syracuse University Press, New York.

Williams, L. H. 1973a. Identifying wood-destroying beetles. Pest Control 41(5):30, 32, 34, 36, 38, 40.

Williams, L. H. 1973b. Anobiid beetles should be controlled. Pest Control 41(6):18, 20, 22, 38, 40, 42, 44.

Williams, L. H. 1973c. Recognition and control of wood destroying beetles. Pest Control 41(2): 24, 26, 28.

Williams, L. H. 1980. Changes in wood processing and use have influenced the likelihood of beetle infestations in seasoned wood. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. SO-28. 10 p.

Williams, L. H., and R. V. Smythe. 1978. Wood-destroying beetle treatment incidence in Arkansas and Georgia during 1962 and 1967 with estimated losses caused by beetles for 11 Southern States during 1970. U.S. Dep. Agric. For. Serv. Res. Pap. SO-143. 8 p.

Williams, L. H., and R. V. Smythe, 1979. Estimated losses caused by wood products insects during 1970 for single-family dwellings in 11 Southern States. U.S. Dep. Agric., For. Serv. Res. Pap. SO-145. 10 p.

Wilson, C. L. 1963. Wilting of persimmons caused by *Cephalosporium diospyri*. Phytopathology 53:1402-4106.

Wilson, C. L., C. E. Seliskar, and C. R. Krause. 1972. Mycoplasmalike bodies associated with elm phloem necrosis. Phytopathology 62:140-143.

Wright, C. G. 1960. Biology of the southern Lyctus beetle, *Lyctus planicollis*. Entomol. Soc. Amer. Ann. 53(3):285-292.

Zainal, A. S. 1978. A new explanation for soft rot cavity formation in the S_2 layer of wood cell walls. Wood Sci. Technol. 12:105-110.

Zinkel, D. F., J. C. Ward, and B. F. Kukachka. 1969. Odor problems from some plywoods. For. Prod. J. 19(12):60.

Zoch, L. L., Jr., E. L. Springer, and G. J. Hajny. 1976. Storage of aspen whole-tree chips under laboratory conditions. U.S. Dep. Agric. For. Serv., Res. Pap. FPL 288. 6 p.

12

Defects and Grades of Trees and Logs

Section 12-4 contains condensed excerpts from a publication by F.J. Petro. Section 12-5 is condensed from an Agriculture Handbook written by C.R. Lockard, J.A. Putnam, and R.D. Carpenter. Sections 12-6, 12-7, and 12-8 are expanded from a review by J.G. Schroeder.

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CHAPTER 12

Defects and Grades of Trees and Logs

Defects in hardwoods that grow where southern pine grows are critically important to their use for lumber, crossties, pallets, veneer, tool handles, and mine timbers. These hardwoods will also be used for pulp, fiberboard, and flakeboard, or burned for industrial energy, and perhaps converted to liquid or gaseous fuels. Most defects are much less important to the latter uses.

12-1 TREE SIZE AND PROPORTIONS

As they affect harvesting cost, tree size and proportions are of interest to manufacturers using hardwoods for any of these products. For ease and completeness of harvesting, trees with undivided central stems typical of **excurrent growth** (fig. 3-56) such as sweetgum, black tupelo, yellow-poplar, sweetbay, and hackberry may be preferred over those with forked stems typical of **decurrent (deliquescent) growth** (fig. 3-35) such as the oaks, hickories, elms, and red maple.

Pine-site hardwoods are small. Of volume in trees 5 inches and larger in dbh, nearly half (46 percent) is in trees under 11 inches, about 29 percent in trees 11.0 to 14.9 inches, and only 25 percent in trees 15.0 inches dbh or larger (Murphy and Knight 1974). Stems of these trees taper about 1¼ inches per 8 feet of stem length.

Not only are stems of eastern hardwoods small, but crook and irregular cross sections diminish yield and value of timbers or lumber sawn from many of them (figs. 22-50 through 22-52). Church (1973) found sweep of 2 inches or more in 17 percent of 4,510 logs measured at Appalachian sawmills; sweep reduced scaled volume at least 10 percent in one out of every seven logs, and at least 15 percent in one of every nine logs measured.

High water content (over 110 percent, dry-weight basis) in some species, e.g., sweetgum and yellow-poplar (table 8-2), raises transport costs per ton of dry fiber compared with woods such as the ashes with water content as low as 47 percent; it also reduces energy recoverable during burning of green wood, and may increase costs of drying fibers, flakes, veneer, or lumber. Species with high bark content such as the oaks (table 16-10), require transport of much low-value bark (about 20 percent of stemwood weight in 6-inch trees) to yield needed quantities of higher-value stemwood. Barks of some hardwoods, particularly hickories and elms, are stringy and cause such problems at the debarker that their use is avoided at many mills.

12-2 WOOD QUALITY

Some uses for hardwoods are limited not only by their size and proportions, but also by anatomical, physical, or chemical attributes. For example, southern red oak is so permeable (table 8-15) that it cannot be used for bourbon barrels, whereas white oak is impermeable and well suited for this use. Black tupelo and other diffuse-porous hardwoods are usable in preparation of dissolving-grade cellulose, but ring-porous hardwoods are not, by the prehydrolysis kraft process. Some southern oaks (fig. 5-22 and 5-52 bottom left) are rarely used for certain papers and fiberboards because their short, large-diameter vessel elements cause rough surfaces.

Tension wood (figs. 5-71 and 5-72) may cause excessive warping of hardwood lumber unless unusual measures are taken (fig. 22-63). The interlocked grain of black tupelo causes low tensile strength in flakes cut from it, diminishing value of the wood for structural flakeboard.

Tangential shrinkage of stemwood, when ovendried from green condition, exceeds 10 percent in most of the oaks, the elms, the hickories, and in sweetgum (table 8-10); shrinkage of such magnitude can significantly degrade lumber during drying and calls for extraordinary procedures (fig. 20-3 bottom). Growth stresses frequently present in post oak, water oak, hickory, white ash, and other species cause boards and cants to distort as they are sawn—a problem for mill operators (Yao 1979).

Stemwood from small trees of 11 major species of pine-site hardwoods—nine oaks, hickory, and winged elm—exceeds 0.6 in specific gravity (table 7-7), and is therefore difficult to manufacture into flakeboard of acceptable density.

Most hardwoods found where southern pines grow are strong stiff woods, but a few, e.g., hackberry, southern red oak, sweetbay, black tupelo, and yellow-poplar have modulus of rupture of 11,000 psi or less when at 12 percent moisture content (table 10-6), and hackberry and black tupelo have modulus of elasticity of only about 1,200,000 psi. Woods of the various species differ greatly in suitability for bending (table 19-1); some are brash and cannot be successfully bent (fig. 19-1).

The chemical composition of some hardwoods may limit usage. Chemical discoloration prevalent in red maple and yellow-poplar prevents acceptance of some wood of these species in appearance-grade products. (See discussion related to figures 9-6 through 9-10.) Color contrast between heartwood and sapwood may preclude use for some products (fig. 5-16). The grey-brown chemical stain prevalent in hackberry lumber requires special control measures.

Some woods have much greater ash content than others. Stemwood of hackberry, hickory, and blackjack oak exceeds 1 percent ash content, and stembark ash content exceeds 10 percent in American elm, winged elm, hackberry, post oak, and white oak (table 6-18). Mineral content, which may affect pulping processes, varies significantly with species (table 6-19).

Acidic woods—those with low pH—may be difficult to bond into durable flakeboard. Stemwood of seven of the oaks has pH lower than 4.9 (table 6-23). Stembark of four species (red maple, blackjack oak, northern red oak, and scarlet oak) has pH of less than 5.0.

Yields from chemical pulping processes are proportional to cellulose content. Pine-site hardwoods vary significantly in this respect (table 6-1); e.g., white ash from southeastern Georgia was found to contain about 49 percent cellulose, while blackjack oak had only about 34 percent.

Sugar content of many of the pine-site hardwoods may preclude their use in panels bonded with portland cement. (See sect. 24-25 and discussion related to figs. 24-64 through 24-67).

12-3 ROT, SHAKES, AND INSECT DAMAGE

Tree diseases and trunk rots are described in section 11-4 and illustrated in figures 11-10 through 11-17. Most southern hardwood trees (84 percent) with fire scars more than 2 inches wide develop butt rot; length of rot above a fire scar is species dependent and positively correlated with age of scar, height of butt bulge, height of rotted butt hollow, and diameter of rot showing on the stump. Percent of cull related to fire-scar severity is given in tables 11-2 and 11-3 and related discussion.

Shake, a separation of annual growth sheaths arising from non-pathogenic causes, can be present in standing trees without external defect; thus, the logger is unable to exclude shake-defective trees from his cut. Tree species vary in their susceptibility to shake, e.g., in Missouri, white oaks are more shake-free than either black or red oaks.

Of the many insects that attack pine-site hardwoods, trunk borers do the most damage because their larvae construct galleries in the wood of living trees, damaging merchantable stem portions—especially butt logs. (see table 11-5, figures 11-25 through 11-31, and related discussion).

12-4 DEFECTS RELATED TO FELLING AND BUCKING[1]

Conventional undercuts (fig. 12-1 bottom) produce butt logs with bevelled ends, reducing the length of a significant number of boards cut from such logs. The Humboldt undercut (fig. 12-1 top) yields butt logs with square ends, eliminating such loss. Loss of board length is minimized in upper logs if bucking cuts are made in a plane perpendicular to tree pith.

The Humboldt undercut of about one-third the tree diameter combined with a correct back cut is the best way of felling hardwoods. Shallow undercuts and back cuts that slope or are lower than the undercut (fig. 12-2) cause splintering that diminishes lumber recoverable from valuable butt logs.

If, after felling, a large tree is supported at two points, it must be bucked with a correct sequence of cuts (fig. 12-3 top) to prevent stem split. Since the initial upper cut must proceed some distance into the log, a wedge should be driven into the cut to prevent binding of the saw. The saw is then withdrawn and the undercut is made. On smaller trees, an undercut only is often satisfactory.

When possible, trees should be felled so that major stem forks form a plane parallel to the ground when they strike; this orientation diminishes risk of stem splits at the fork. Trees with forks or a number of large branches in the crown sometimes fall so that one of the larger branches is upright. To relieve stress and prevent stem split, larger branches acting on the tree stem should be cut off before the stem is bucked into logs (fig. 12-3 bottom).

If sound wood around butt rot is so narrow that all or most of it would be slabbed off in the sawmill, the defect should be cut off in the woods; some such short defective butts can be sawn profitably on a bolter saw, however (see sect. 28-4).

The amount of interior cull in stem bulges is variable and difficult to assess (see sect 12-5), but a bulge should never be placed midway between log ends. For highest quality logs bulges should be eliminated by crosscutting out the defective section. Alternatively a bulge can be placed at one end of a log where, if necessary, individual boards can be end trimmed to remove defects.

An understanding of knot structure and location is required to correctly buck tree stems into logs of optimum value. In a typical straight hardwood tree measuring about 15 inches dbh, the defect zone in the lower stem has the shape of an inverted cone, with branch knots becoming coarser and more prominent as height above ground increases (fig. 12-4AB). The clear zone that produces high quality lumber is widest at the stump, and narrows as height increases. This results from natural pruning of lower branches while the tree is a sapling; branch bases (knots) are smaller and more deeply overgrown with clear wood than the larger knots further up the tree. The high quality of the wood in the butt section is frequently indicated by absence of bumps, irregular bark patterns, or other surface disturbances.

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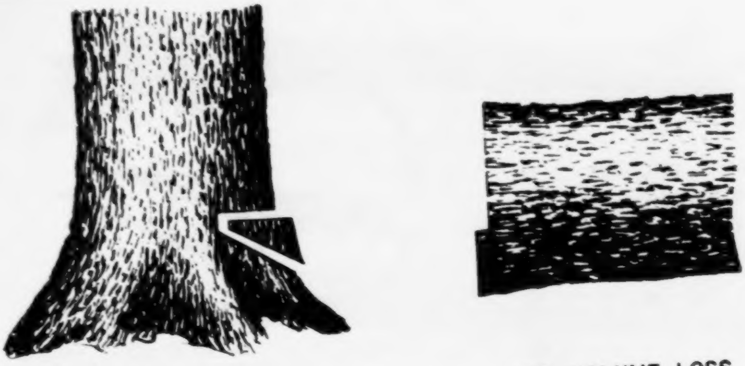
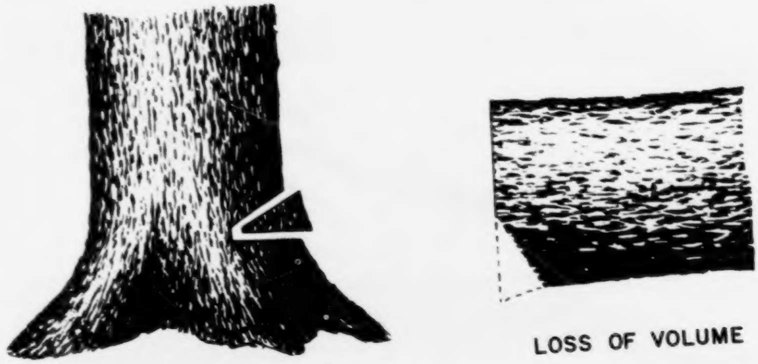
[1] This section contains condensed excerpts from Petro (1975); readers interested in a more complete discussion of felling and bucking hardwoods should consult the source publication.



HUMBOLT UNDERCUT

NO VOLUME LOSS



CONVENTIONAL UNDERCUT

LOSS OF VOLUME

Figure 12-1.—Two common types of undercuts used in felling hardwoods. (Drawing after Petro 1975.)

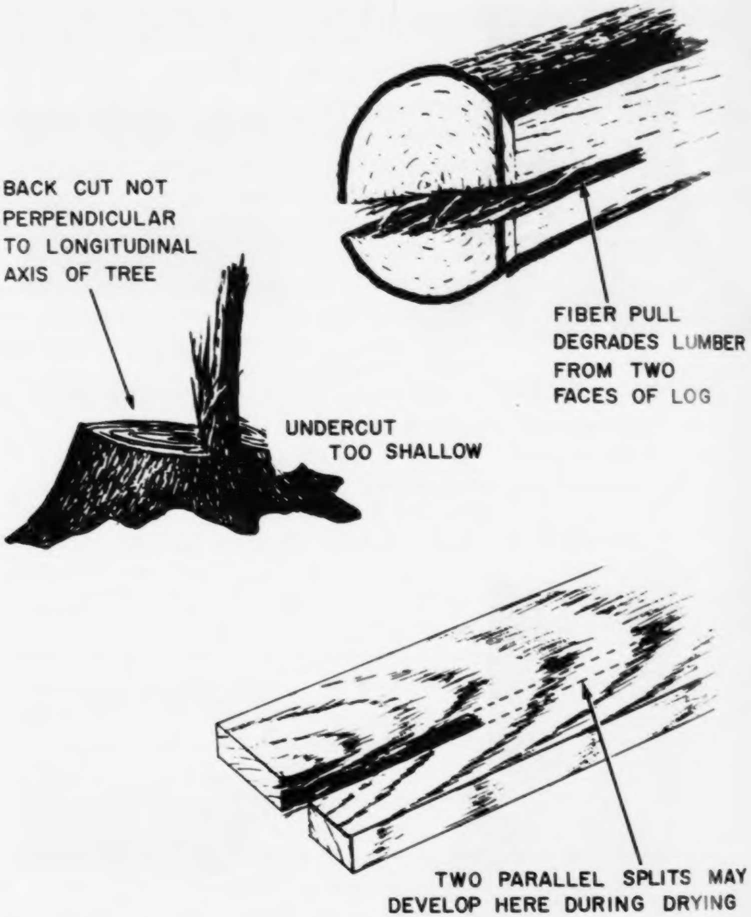
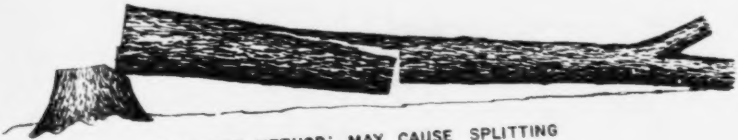
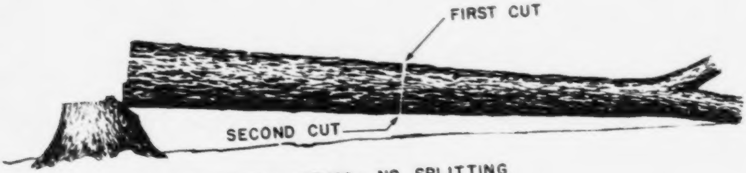

BACK CUT NOT PERPENDICULAR TO LONGITUDINAL AXIS OF TREE
FIBER PULL DEGRADES LUMBER FROM TWO FACES OF LOG
UNDERCUT TOO SHALLOW
TWO PARALLEL SPLITS MAY DEVELOP HERE DURING DRYING

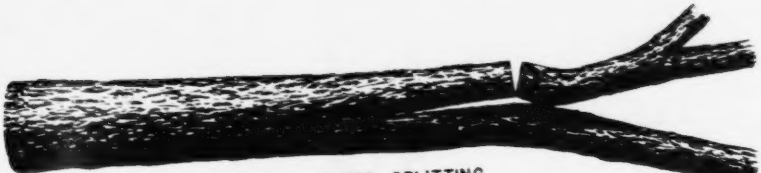
Figure 12-2.—Improper felling method often resulting in splinter pull. (Drawing after Petro 1975.)



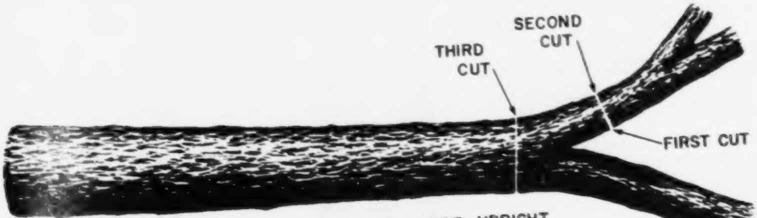
INCORRECT METHOD: MAY CAUSE SPLITTING


FIRST CUT
SECOND CUT

CORRECT METHOD: NO SPLITTING



INCORRECT METHOD: OFTEN CAUSES SPLITTING


SECOND CUT
THIRD CUT
FIRST CUT

CORRECT METHOD: REMOVE LARGE UPRIGHT BRANCHES FIRST

Figure 12-3.—(Top) Method of bucking trees supported at two points. (Bottom) bucking forked trees. (Drawings after Petro 1975.)

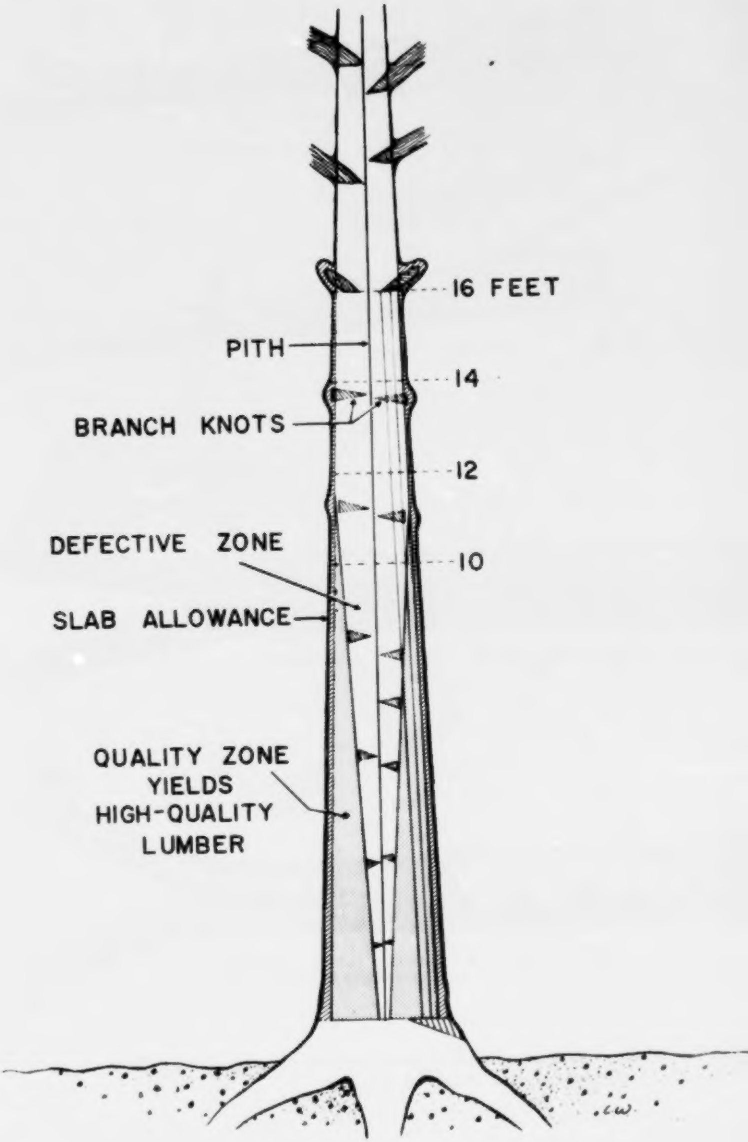

16 FEET
PITH
14
BRANCH KNOTS
12
DEFECTIVE ZONE
10
SLAB ALLOWANCE
QUALITY ZONE YIELDS HIGH-QUALITY LUMBER

Figure 12-4A.—Typical medium-size hardwood tree showing knot structure and over
growth to form a clear-wood zone in the butt log. (Drawing after Petro 1975.)

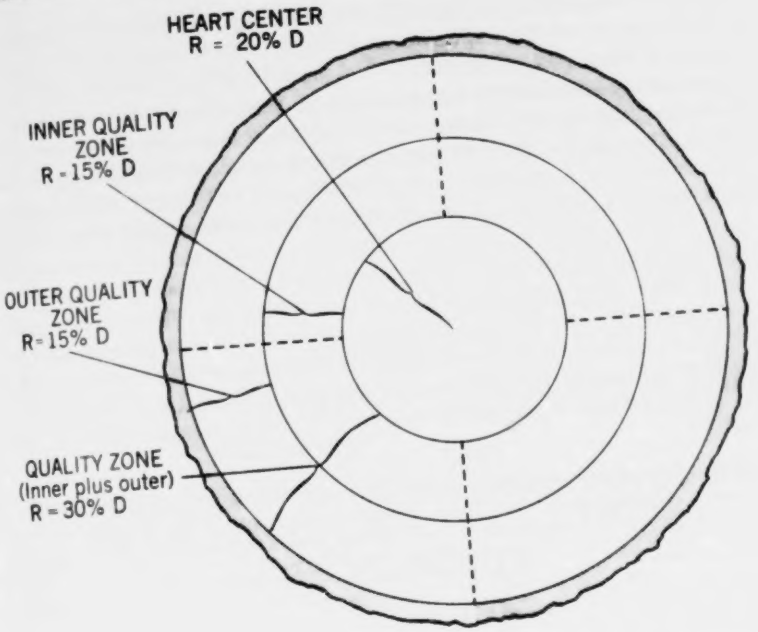

HEART CENTER
R = 20% D
INNER QUALITY ZONE
R = 15% D
OUTER QUALITY ZONE
R = 15% D
QUALITY ZONE
(Inner plus outer)
R = 30% D

Figure 12-4B.—Three zones in ends of hardwood factory lumber logs that relate to defect occurrence. (Drawing after Rast et al. 1973.)

In the tree diagrammed in figure 12-4A, some slight bark distortion may be evident below the 10-foot mark, but may be unimportant because the underlying defect is deeply buried. Around the 11-foot mark, however, distinctive patterns of concentric circles indicate overgrown branch knots closer to the surface. At the 14-foot mark, the two medium bumps indicate branch knots adjacent to the surface. The high bumps at 16 feet are obvious indicators of branch knots.

When stems are crooked, as is frequently the case with pine-site hardwoods, crosscuts should be located to produce the straightest logs possible (fig. 12-5).

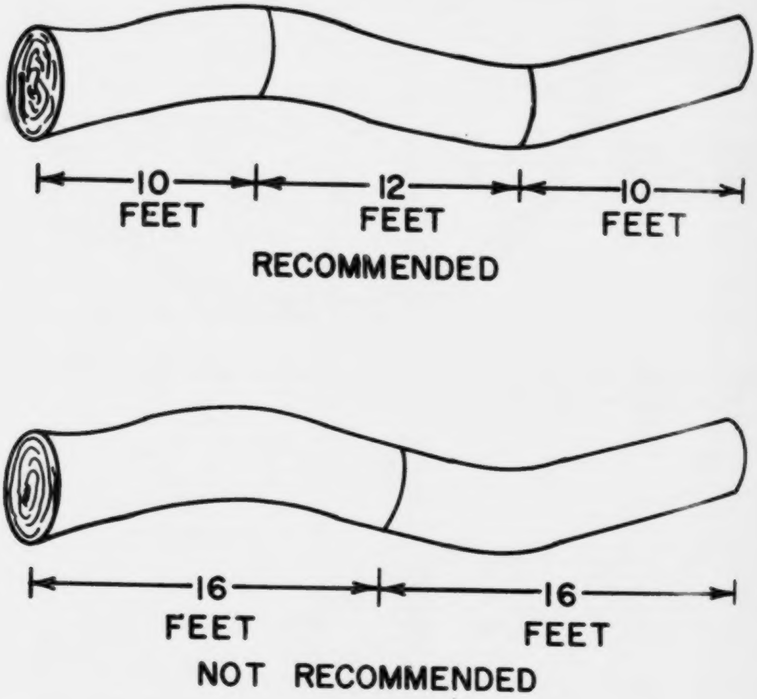


Figure 12-5.—Recommended practice for bucking crooked stems into logs, compared with poor practice. (Drawing after Petro 1975.)

12-5 TREE-RELATED DEFECTS[2]

Perfect trees are rare and poor trees are abundant. Determination of the lower limit of tree or log merchantability is important to economic success when harvesting high-priced hardwood timber of variable quality. Merchantability is judged on the basis of size, straightness, smoothness, freedom from rot and shake, and of type, location, and concentration of log defects—many of which may be inconspicuous.

More broadly, quality of a log or tree is determined by those properties that make it suitable for conversion into particular products; definitions of quality vary between end products. Thus end products or use classes must be specified before quality of a log or tree can be evaluated. Use classes are more completely defined in section 12-6, but those shown in figure 12-6 will serve for preliminary discussion of tree related defects as they affect logs for lumber and veneer.

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[2] This section is condensed from Lockard et al. (1963); major text portions are reproduced here with only minor editorial changes. Readers needing more detail should consult the source reference. Those particularly interested in tree related defects as they affect large hardwood veneer logs should consult Harrar and Campbell (1966). Useful, but published too recently for incorporation into this text, is: Rast, E.D. 1982. Photographic guide of selected external defect indicators and associated internal defects in northern red oak. U.S. Dep. Agric., For. Serv. Res. Pap. NE-511. 20 p.

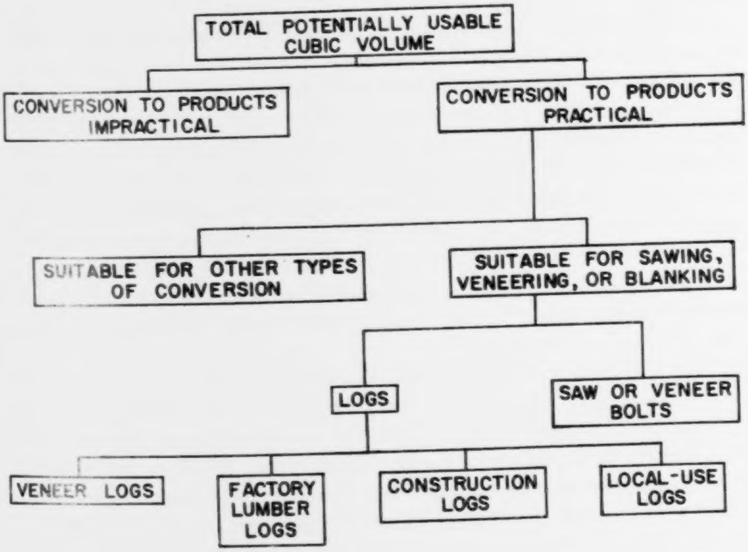
TOTAL POTENTIALLY USABLE CUBIC VOLUME
CONVERSION TO PRODUCTS IMPRACTICAL
CONVERSION TO PRODUCTS PRACTICAL
SUITABLE FOR OTHER TYPES OF CONVERSION
SUITABLE FOR SAWING, VENEERING, OR BLANKING
LOGS
SAW OR VENEER BOLTS
VENEER LOGS
FACTORY LUMBER LOGS
CONSTRUCTION LOGS
LOCAL-USE LOGS

Figure 12-6.—Potential products obtainable from foliage-free, above-ground portions of a hardwood tree. (Drawing after Rast et al. 1973.)

Trees do not grow into perfectly straight cylindrical form containing only perfect wood, and it is not realistic to consider such a model as a standard. A more practical standard for a high-quality sawlog might be as follows:

- It is 16 feet long and 24 inches or more in diameter at the top end.
- It is straight, but with slight taper and butt flare.
- The wood is straight grained. There is no requirement as to other characteristics of the wood, i.e., whether heart or sap, uniform or variable in density or color.
- The log has a "heart center" within a central cylinder of diameter not more than 40 percent of the log diameter. This heart center contains limb stubs and pith center only; it is free from rot, shake, stain, and similar imperfections.
- Between the heart center and the slab is a **quality zone** in which there are no imperfections such as knots, holes, bark pockets, mineral stain, or rot.

Standard products of high value will be cut from such a log. Any deviation from these specifications, except for a moderate one in size, will reduce average value of potential products. The deviations that are most important, occur most frequently, and—for all practical purposes—determine quality are (1) change in position of log in tree, (2) reduction of size of log, (3) crookedness, and (4) imperfections in either the heart center (except for knots and pith) or in the outer rim of wood.

Position affects quality because the farther up the tree the log is, the larger the heart center, and the coarser the limb stubs in it are likely to be (fig. 12-4).

Change in size, especially in diameter, is very important. It is their typically small size that most often lowers quality in hardwoods that grow among southern pines. Small-diameter logs yield a high proportion of products containing the coarse heart-center blemishes. If made into standard factory lumber, large-diameter logs will yield wider and more valuable boards; the wider the boards, the greater the possibility of raising values by primary ripping to eliminate or segregate blemishes. Similarly, large timbers, which can be cut only from large logs, are more valuable per unit than smaller ones. Changes in length are not so important in the individual log, for the highest grade of lumber permits pieces of all lengths down to 8 feet. There are, however, definite limitations on the percentages of short lengths that can be included in large shipments of a given grade, and there is sometimes a premium on shipments containing all long lengths (14 feet and 16 feet).

For logs of a given position and size, **crookedness** is an important cause of reduced product value. There are two variations of this. One is **sweep,** a gradual curvature from a straight line drawn from one end of the log to the other; the other is a sharp deviation within the log, called **crook.** Either sweep or crook may cause opening-cut saw lines to pass through the low-grade center zone, reducing product value by causing an abnormal distribution of core defects. They also reduce recoverable volume of product and increase production costs because crooked logs are hard to handle on rollways, are difficult to fit into loads, and increase sawing time.

DEFECTS OF TREES AND LOGS

Common deviations from the ideal standard hardwood log include imperfections in the slab, quality, or heart-center zones (figs. 12-4A and 12-4B). These imperfections fall into two main categories: (1) **scaling defects** such as rot, shake, checks, sweep, and crook, which reduce the usable volume of the log or tree, and (2) **grade defects** such as knots, stain, holes, and bark pockets which affect the appearance or strength of the final product.

Schroeder (1981) notes that distribution between the two defect categories is not always clear cut, e.g., if rot exceeds an established allowable amount in a log, it becomes a grade defect in that it either lowers the grade of the log or eliminates it from that use class. Whether an abnormality is considered a grading defect often depends on the intended use class of the log or tree (table 12-1). For example, small sound knots are grading defects in factory lumber logs, but not in construction or local use logs.

Usage gives the term "grade defect" to abnormalities or irregularities on the log surface as well as to imperfections in the wood. These outside features are really indicators of imperfections in the underlying wood and could be termed "grade defect indicators." For example, a branch stub is an indicator of a knot in the product to be sawed from the log. Nevertheless, because timber appraisers deal with logs or tree stems as such, and not as sawn products, this publication designates these surface features as **log grade defects** or **degraders.** On the other hand, imperfections in the wood are designated as **product grade defects.**

CLASSES OF LOG ABNORMALITIES

Log abnormalities can be divided into two general classes: those found on the surface of the log and those found on the ends. Some abnormalities are superficial, i.e., they are in the slab zone (an outer zone less than one-tenth the log diameter in thickness), and may be disregarded. In standing timber, abnormalities may be disregarded if they will not be included in the logs that are to be harvested.

TABLE 12-1.—*Classification of surface abnormalities in logs for three uses* (Rast et al. 1973)

Abnormalities	Factory Logs •	Construction Logs	Local-Use Logs
Log surface			
Bulges:			
Butt	Defect	Defect	No defect
Stem	Defect	Defect	No defect
Bumps:			
High	Defect	(3)	(3)
Medium	Defect	(3)	(3)
Low	(2)	(3)	(3)
Burl	Defect	Defect	(3)
Butt scar	Defect	(3)	No defect
Butt swell	No defect	(3)	(3)
Canker	Defect	Defect	No defect
Conk	Defect	Defect	No defect
Dormant buds	(2)	No defect	No defect
Epicormic branches	(2)	No defect	No defect
Flanges	No defect	No defect	No defect
Flutes	(3)	(3)	No defect
Fork	Defect	Defect	No defect
Gum lesions	(3)	No defect	No defect
Holes:			
Large	Defect	(3)	(3)
Medium:			
Bark scarrer, fresh	No defect	No defect	No defect
Bark scarrer, old	Defect	No defect	No defect
Birds, light	No defect	No defect	No defect
Birds, heavy	Defect	No defect	No defect
Grub	(2)	No defect	No defect
Increment borer	Defect	No defect	No defect
Tap	Defect	No defect	No defect
Small	(3)	No defect	No defect
Log knots:			
Sound	Defect	(3)	(3)
Unsound	Defect	(3)	(3)
Limbs	Defect	(3)	(3)
Overgrowths:			
Knots & bark pockets	Defect	(3)	No defect
Insects	Defect	No defect	No defect
Bird peck	Defect	No defect	No defect
Bark distortions:			
Heavy or medium	Defect	No defect	No defect
Light	No defect	No defect	No defect
Seams	(2)	(3)	No defect
Splits	(3)	(3)	No defect
Surface rise	No defect	No defect	No defect
Wounds:			
New	No defect	No defect	No defect
Old	(3)	(3)	No defect

TABLE 12-1.—*Classification of surface abnormalities in logs for three uses* (Rast et al. 1973)—Continued

Abnormalities	Factory Logs	Construction Logs	Local-Use Logs
Log end			
Bird peck	(2)	No defect	No defect
Bark pocket (crotch)	Defect	Defect	No defect
Double pith	No defect	Defect	No defect
Grease spots	(2)	No defect	No defect
Grub channels	(2)	(3)	No defect
Gum spots	(2)	No defect	No defect
Loose heart	(1)	Defect	No defect
Rot	(2)	Defect	No defect
Shake:			
Ring	(2)	Defect	No defect
Wind	(2)	Defect	No defect
Soak	(3)	No defect	No defect
Spider heart	(2)	Defect	No defect
Stain	(2)	No defect	No defect
Worm holes:			
Pin, flag & shot	Defect	No defect	No defect

---

[1] Defect if not confined to heart center and inner quality zone.

[2] Refer to special instructions at end of discussion under paragraph head *Grading factory lumber logs* of sub-section FACTORY LUMBER LOG GRADES in section 12-6.

[3] Refer to discussion of these defects in section 12-5.

LOG SURFACE ABNORMALITIES

Log surface abnormalities, like end abnormalities, are important grade indicators, but there is a better chance of observing indicators of wood blemishes on the surface than of seeing the blemishes themselves on the log end. Moreover, the distribution and frequency of product grade defects can be judged best from the surface indicators. These indicators include bulges, bumps, burls, butt scars, butt swell, canker, conk, epicormic branches and adventitious bud clusters, flanges, flutes, forks, gum lesions, holes, log knots, limbs, overgrowths, seams, splits, surface rises, and wounds.

Bulge.—A **bulge** is a general enlargement of the stem of a tree or log, in the nature of a "barreling" effect, often without an obvious cause such as knot or callus formation. It may be near a wound, rotten knot, knothole, or other point of entry for rot. It generally indicates a cull section with the extent of the rot shown by the extreme limits of the deformation. There are two types of bulges, butt bulge and stem bulge (fig. 11-12 bottom left and 12-7).

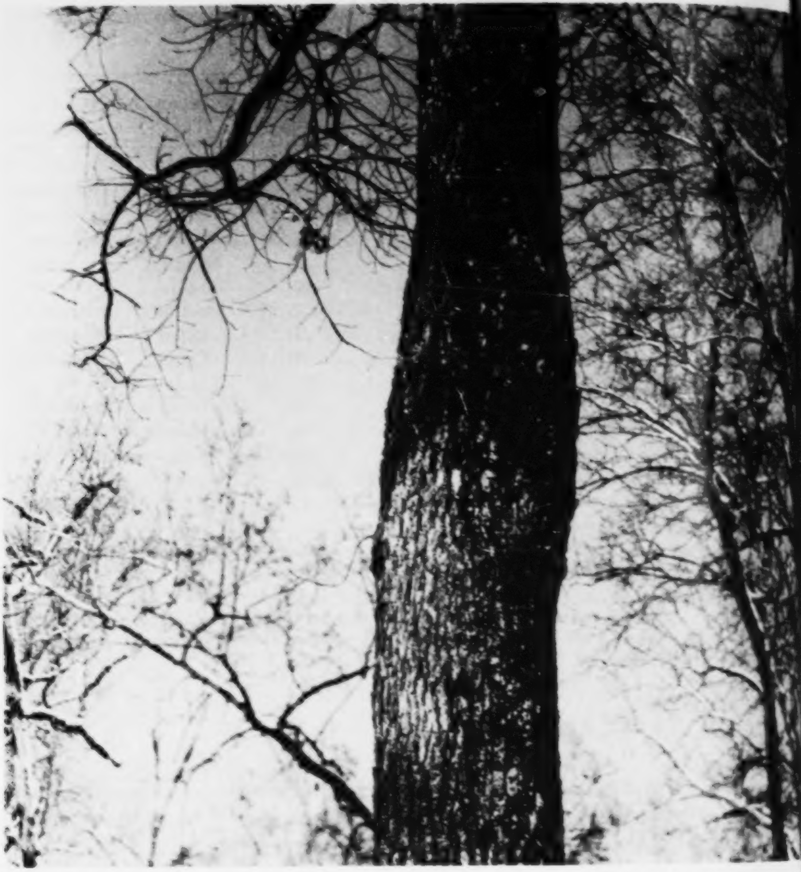

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Figure 12-7.—Stem bulge. (Photo from Lockard et al. 1963.)

Butt bulge is nearly always accompanied by hollow butt. Rot generally extends beyond the hollow, and the upper tapered-off limit of the bulge usually indicates the approximate upper limit of serious rot. Butt bulge has no special relation to species, although it is most frequently conspicuous in the oaks. In sweetgum, elms, and ashes, even considerable butt rot may not cause a clearly defined butt bulge. In these species the bark over even a slight bulge often becomes smoother and darker and scales off faster than in a sound stem. This is especially true in sweetgum.

Stem bulge is not as common as butt bulge, but may be found in any species.

Bulges are evidence of internal rot and under good operating practice are not included in logs. If a stem bulge occurs in the middle of a log, where it cannot be cut out, then that section involved must be scaled out and thus is a degrader in **factory lumber logs**. A stem bulge will disqualify a log otherwise suited for **construction logs.** In **local-use logs** the bulges can be overlooked, provided the accompanying rot does not exceed the scaling deduction limits set for the class.

Bumps.—A **bump** is a protuberance overgrown with bark (fig. 12-8). It may be an abrupt protuberance, or a smooth undulation which gradually tapers back in all directions to the normal contour of the log. A minimum bump is arbitrarily defined as a swell on the surface with a taper steeper than 1 to 6, i.e., it is a bump if the distance from the center to the edge is less than six times the height from the normal contour to the top. If it has a taper flatter than 1 to 6, it is classed as a **surface rise**. Low bumps have tapers from 1 to 6 to 1 to 3; high bumps have a taper sharper than 1 to 3. Abrupt bumps taper less than 1 to 1½.

Bumps may occur on any species. Low bumps are particularly noticeable in red maple, tupelo, soft elm, and the ashes, magnolias, and white oaks. High bumps are conspicuously frequent in white oaks on poor sites.

About nine-tenths of all bumps indicate projecting sound or rotten limb stubs, a cluster of adventitious buds, or an excessive folding or ingrowing of the bark over a scar.

In **factory logs** low bumps can be disregarded in red maple, tupelo, American elm, *Betula* sp., the ashes, magnolias, and white oak. High bumps, however, are degraders in these species. In other species all bumps are degraders, for even low ones cover blemishes that are usually in the quality zone where they limit clear cuttings.

In **construction logs** the effect will depend upon the size of the underlying blemish. If the diameter of a high bump is less than one-third of the diameter of the log at the point where the bump occurs, or if the diameter of the feature underlying the bump is estimated to be less than one-fourth of the width of a face of the largest included timber (judged from the small end of the log), then the abnormality can be disregarded as a grading deffect. If the underlying feature is larger, it is a degrader. In the case of a low bump it is difficult to estimate the size of the underlying blemish. Generally, however, the blemish will be so large that a low bump must be considered a log defect in chestnut, scarlet, black, and water oaks; also in overcup oak *Quercus lyrata* Walt.), pin oak (*Quercus palustris* Muenchh.), and cedar elm (*Ulmus crassifolia* Nutt.). In construction logs of other species, low bumps can be disregarded.

In **local-use logs** bumps of both kinds are degraders if their diameter exceeds one half of the diameter of the log at point of occurrence; otherwise they can be disregarded.

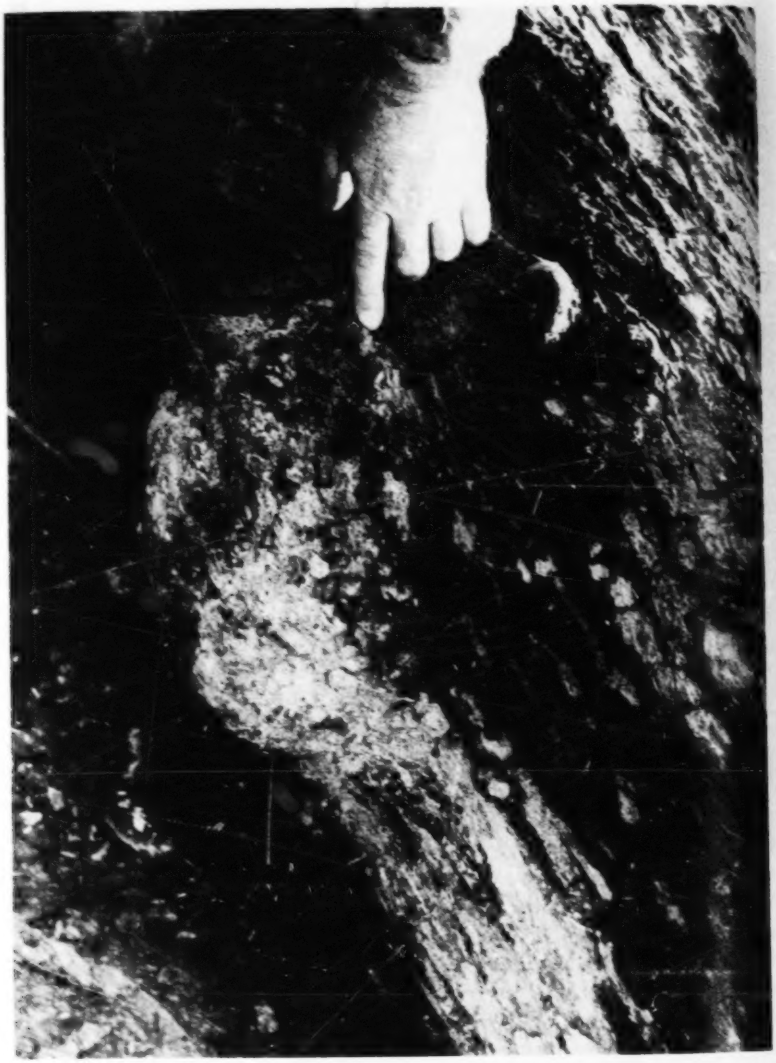

Figure 12-8.—Bump. (Photo from Lockard et al. 1963.)

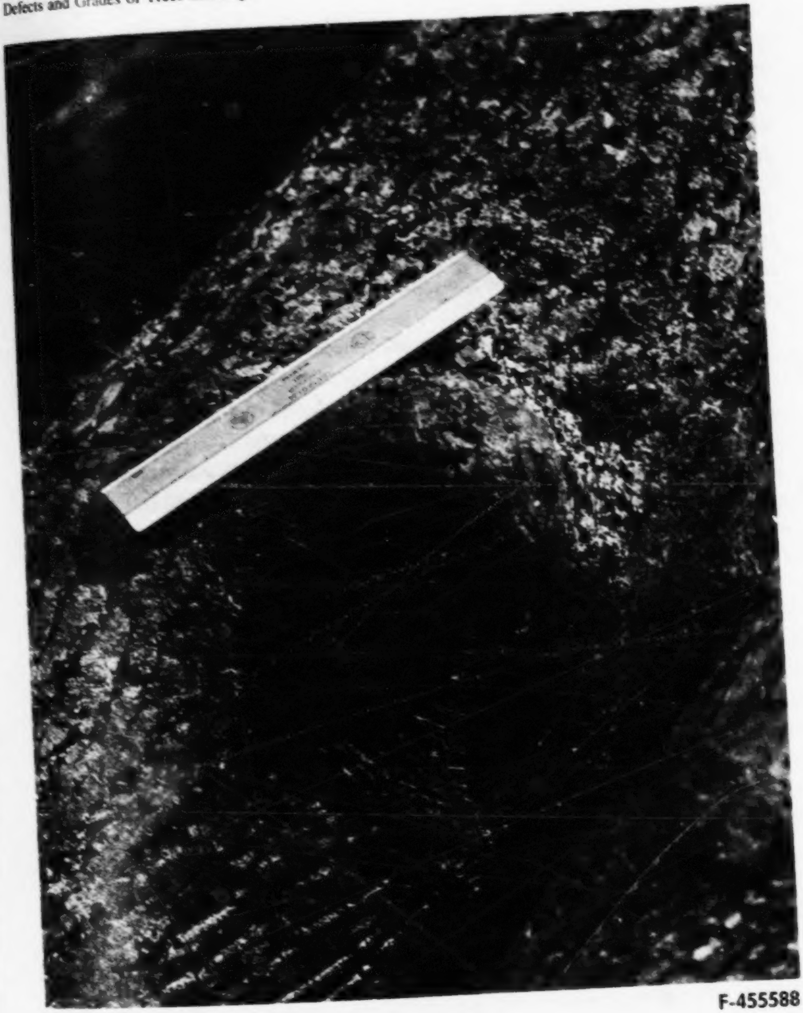

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Figure 12-9.—Burl. (Photo from Lockard et al. 1963.)

Burls.—A **burl** is a sound, hard, woody protuberance on the bole, more or less rounded or horizontally ridged in form, with no protruding limbs, twigs, stubs, or indications thereof (fig. 12-9). It is sometimes related to aborted adventitious buds.

Burls, while uncommon, are most often found on the magnolias (including sweetbay), sugar maple (*Acer saccharum* Marsh.), walnut (*Juglans nigra* L.), and cow oak (*Quercus michauxii* Nutt.). They are occasionally found in yellow-poplar, northern red oak, and yellow birch (*Betula alleghaniensis* Britton).

A true burl is a surface indication that the grain in the wood is distorted into a wavy, curly, or bird's eye effect. Other similar apparently sound abnormalities such as incipient cankers, popularly classed as burls, may contain considerable amounts of bark, rot, twig knots, and even insect channels. In factory logs the true burl, if it can be identified, technically is not a degrader. Nevertheless, because of the difficulty of identifying true burls, all features popularly considered as burls are classed as grading defects in **factory lumber logs**. Since burls would unquestionably weaken **construction material**, they must be considered degraders in these logs. In **local-use logs**, however, they can be disregarded unless they extend half way across the circumference of the log at point of occurrence.

Butt scar.—Butt scars, found on all species, are generally triangular or wigwam-shaped openings at the base of the bole, from a few inches to several feet high (figs. 11-10 and 11-12 bottom right). Scars may show weathered or stained sapwood, rotten heartwood, or may open into a rotten hollow butt. When associated with advanced rot or hollow, a butt scar may be accompanied by a butt bulge (fig. 11-10). Fire is the most common cause, but it can be caused by logging equipment, cattle, or other agent that scrapes bark from the base of the tree. Worm holes which are defects in factory logs, are often associated with butt scars.

Since severe rot is generally associated with butt scars, the log is usually cut above the butt swell. Sometimes, however, a butt scar of recent origin with a limited amount of rotten or stained wood is left on the log. In **factory logs** the area involved is a grading defect even though scale deduction is made for it. In **construction logs** a butt scar may be disregarded if it and the associated rotten wood are superficial and do not enter the included tie or timber. In standing trees butt scar and associated rot may be disregarded if the logs can be cut so as to meet the minimum requirements of the log class. Otherwise, a butt scar is a degrader. Butt scar is not a degrader in **local-use logs.**.

Butt swell.—A **butt swell** is an enlargement of the tree trunk, over and beyond the normal stump flare generally found in all species. It is a normal development, apparently related to wetness of site, but not to injuries. Trees with butt swell are sometimes called "churn-butted" or "bottle-butted."

In standing timber butt swell may be confused with butt bulge. Butt swell is related to site and confined to red maple, green ash, water tupelo (*Nyssa aquatica* L.), and swamp tupelo (*Nyssa sylvatica* var. *biflora* (Walt.) Sarg.). Within the species the degree of butt swell varies according to depth, duration, and seasonal occurrence of water. The wood in the butt swell is sound, whereas in a butt bulge it is very likely to be rotten. In green ash the wood in butt swell may be extremely porous, of very low specific gravity, weak, and brash.

Butt swell is not related to imperfections in the underlying wood. It does not lower lumber grade and thus is not a log grade defect in **factory logs**. Nevertheless, the wood in the swell is often soft enough to limit the use to which the lumber can be put. For instance, green ash lumber cut from swelled butts, although graded by standard rules, is classed in the trade as "cabinet ash" and does not command the high price obtainable for "firm or better" taken from higher in the tree. In **construction** and **local-use logs** of tupelos, the swelled section may be so soft as to be worthless for any purpose at all. Such logs are usually cut above the butt swell.

Canker.—A **canker** is a localized necrotic lesion, primarily of bark and cambium (fig. 11-11). It is common on oaks, hickories, ashes, and on black cherry (*Prunus serotina* Ehrh.) and is usually an entrance for decay fungi.

In good operating practice a canker is not included in the log. Should it be included, it is a definite degrader in a **factory log**. It is a grading defect which will disqualify a log otherwise suitable for **construction material**. An included canker can in itself be disregarded in a **local-use log** unless it contributes to scaling deduction beyond the limit allowed for the class.

Conk.—**Conks**, which may be found on all species, are fibrous, sometimes fleshy excrescences of definite form and structure on the bole (fig. 11-12). They are the fruiting bodies of wood-rotting fungi, and usually indicate serious heart rot.

A conk generally indicates an amount of rot, usually close to or in excess of the percentage of gross log volume allowed in a merchantable log of any type. If the log qualifies as a **factory log**, the conk, together with the associated rotten area, becomes a grading deffect. It will limit cuttings outside of the heart center even though scale deduction is made. In a log otherwise suitable for **construction material** conk is a definite degrader, for it is evidence of rot in the log interior which will disqualify the log. In a **local-use log** the conk can be disregarded, provided the rot with which it is associated does not exceed the scaling deduction limit for the log class.

Epicormic branches and adventitious bud clusters.—**Epicormic branches**, stem from abnormal buds found at points on the stem unrelated to the crown. Knots from such branches do not extend to the pith. They arise from latent or dormant buds persisting within the cortical-cambial zone indefinitely and can be activated at any time in response to various stimuli.

Adventitious bud clusters (fig. 12-10), similar but independent in origin, may arise at any time during the life of a tree. They often originate in the callus tissue resulting from wounding or bruising the cambium layer, but may develop independent of any such mechanical action. Very often they develop into clusters of fine twigs of short life, and in this case they are commonly accompanied by small bark pockets. They are not necessarily repetitious and-are less common on most species than epicormic branches.

They are found most frequently on all species of elm, oak, and maple, and on sweetgum and yellow-poplar.

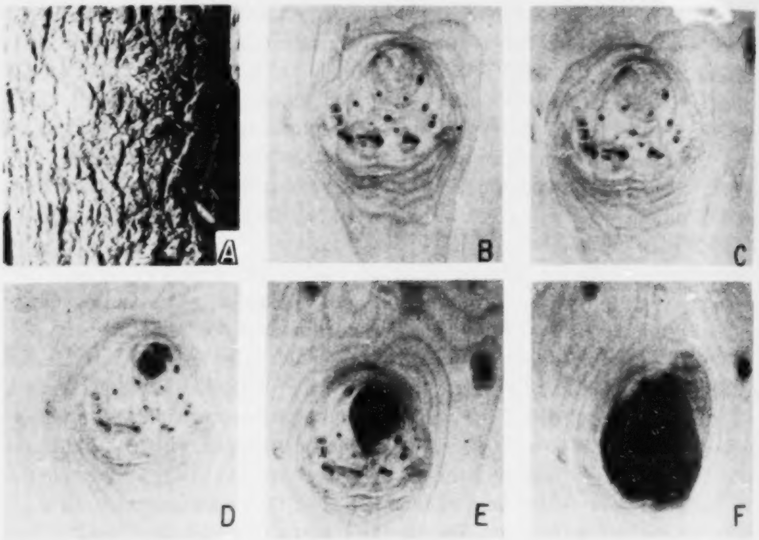

Figure 12-10.—(A) Bark pattern in yellow-poplar above a cluster of adventitious buds. (B,C,D,E,F) Pattern in veneer at 2-inch intervals across the radius of same bolt following rounding of veneer bolt to core. (Photos from Harrar and Campbell 1966.)

Underlying the epicormic branch scar are very small knots, small bark pockets, or both. The twig or branch stub apparent on the surface may not extend very far into the wood. However, a succession of others of similar origin often appears deeper within the log. Wood blemishes caused by either epicormic branch or adventitious branches or bud clusters stop clear cuttings and are log grade defects in **factory logs**. The knots and bark pockets indicated by bud clusters are not degraders in **construction logs** and in **local-use logs.**

Flanges.—Flanges, common in elms, water oak, and red maple, are buttress or wing-like formations at the base of the tree. They are exaggerated projections or convolutions of the normal stump flare and usually extend up the bole beyond normal stump height, sometimes 4 or 5 feet from the ground. They appear to be related to wet and soft ground.

The wood in flanges is in the slab zone of saw logs and the round-up zone in veneer logs. Moreover, flanges do not indicate blemishes or imperfections in underlying wood. They are therefore not log grade defects in any type of log.

Flutes.—Flutes, most exaggerated in soft elms, are also common in red maple and occur occasionally in water oak, pecan (*Carya* sp.), and *Magnolia* sp. They are folds or convolutions of the surface of the trunk running up and down (fig. 12-11), occasionally extending up into the second log. They generally include ingrown bark. They appear to be of normal origin, related to softness of site, much as flanges are.

Flutes usually do not extend deeply into the log at the small end. When they do not, they may be disregarded in all classes of logs. In **local use logs** they may be disregarded in any case.

Fork.—A fork is a crotch between double tops (fig. 12-12), sometimes included by error when logs are bucked to arbitrary lengths.

A hidden effect of a fork is double pith, and generally, a bark pocket. In the fork portion grade outturn and volume yield are both lowered significantly. In **construction logs** a scaling deduction for a section should be made back to a point behind the separation. In **factory logs** the seam and any enclosed bark should be scaled out following the standard practice for deducting for interior scaling defect; but if the portion scaled out is so large that it precludes cuttings, then the fork is a log grading defect. In standing timber, however, a fork is not a degrader if logs that fulfill the minimum requirements for the log class can be cut. Forks can be disregarded in **local-use logs** except for a scaling deduction.

Gum lesions.—Gum lesions, groups of abnormal small wounds on stems, are found most frequently in sweetgum growing near the southern extremity of its range, and on black cherry (*Prunus serotina* Ehrh.). Ashes, tupelos, and persimmon (*Diospyros virginiana* L.) are occasionally affected. The lesions heal over each year, but new ones form in the same area year after year.

In sweetgum lesions, a fungus (*Botyryosphaeria ribis*) kills and dissolves strips of cambium tissue, and black liquid storax oozes out of the bark fissures. Healing results in coarse vertical folds of ingrown bark (fig. 12-13).

Gum spots in sweetgum differ from lesions in that they are caused by cambium-mining insects. Ingrown bark is seldom associated with gum spots. In black cherry, lesions that exude gum result from at least two species of cambium-mining insects.

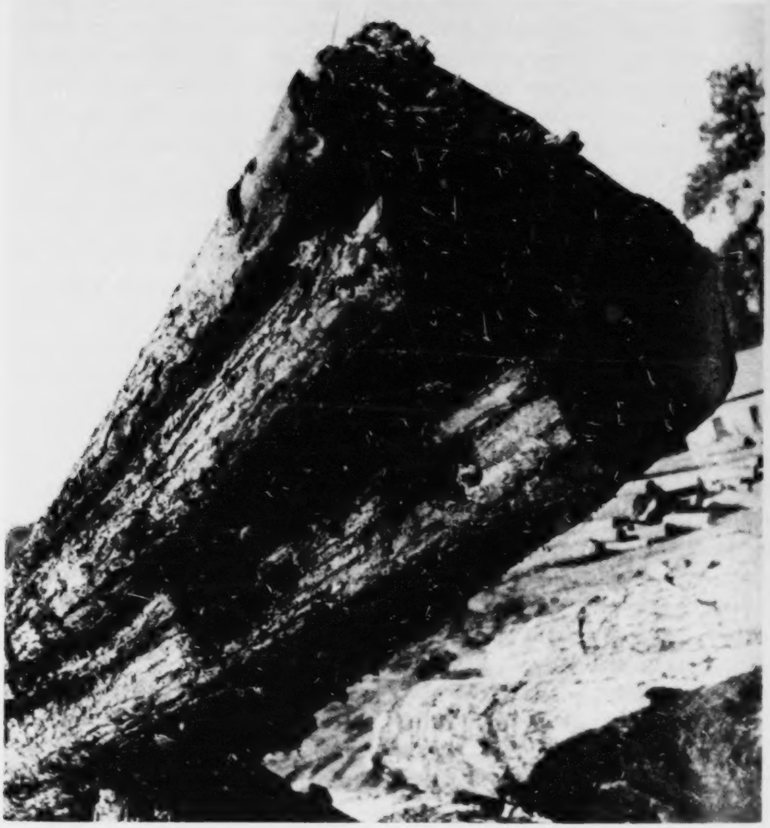

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Figure 12-11.—Flutes. (Photo from Lockard et al. 1963.)

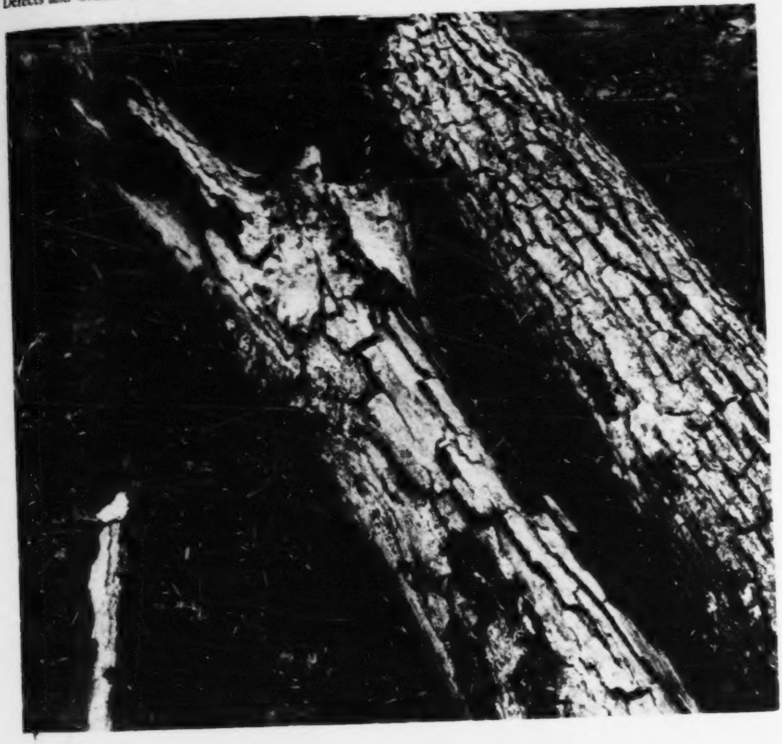

Figure 12-12.—Fork included, by error in bucking, on white oak log at left.

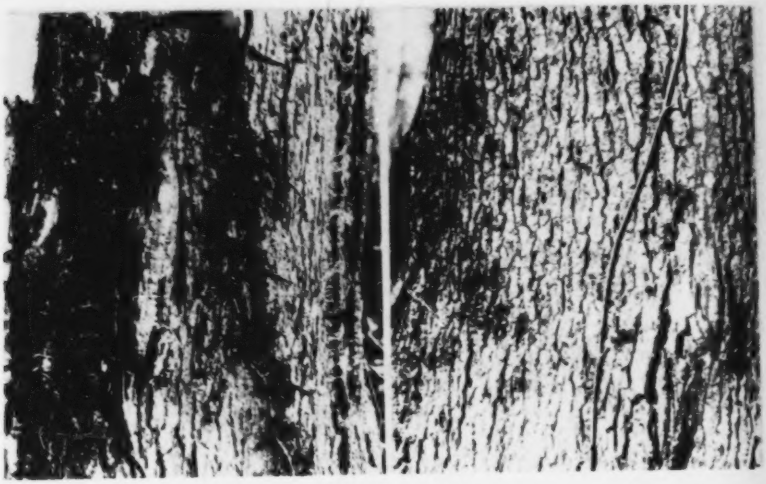

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Figure 12-13.—(A) Healed bark lesion in sweetgum of the lower Coastal Plains showing prominent rib of abnormal wood and folded bark projecting above surface of log. These ribs become buried and hidden in large trees and result in encased bark pockets—serious defects when the trees are cut into veneer and factory lumber. (B) Older healed bark lesions partially buried in the trunk of Coastal sweetgum. These indicate areas of abnormal wood, ingrown bark, and black-stained wood which seriously degrade veneer and factory lumber. Much more dense concentrations and/or coarser lesions occasionally occur which make short sections of bole unfit for construction logs and sometimes, even for pulpwood. (Photos from Lockard et al. 1963.)

Underlying gummy surfaces are many small bark pockets and gum streaks in the wood. Wood blemishes caused by all of these lesions stop clear cuttings and are grade defects in **factory logs** in sweetgum. The highest grades of black cherry lumber, however, admit gum in the "clear face" cuttings, and the lumber is graded "sap and gum—no defect." Therefore, gum lesions are not degraders in black cherry factory lumber logs. They may be disregarded in **construction** and **local-use logs** of both species.

Large holes.—Large holes, found in all species, are unoccluded openings over ½-inch in diameter (figs. 11-12 top right, and 12-14). Among their causes are rotten knots, woodpeckers' excavations, and mechanical damage.

In **factory logs** all large holes are log grade defects. In **construction logs** they are degraders if their size is over one-third the diameter of the log at the point of occurrence, or if, regardless of size, they extend more than 3 inches into the included timber. If they are smaller or shallower than this, they may be disregarded, provided they are surrounded by sound wood. Otherwise, they are grading defects. In **local-use logs** large holes may be disregarded unless their size is over one-half the diameter of the log at the point where the hole occurs.

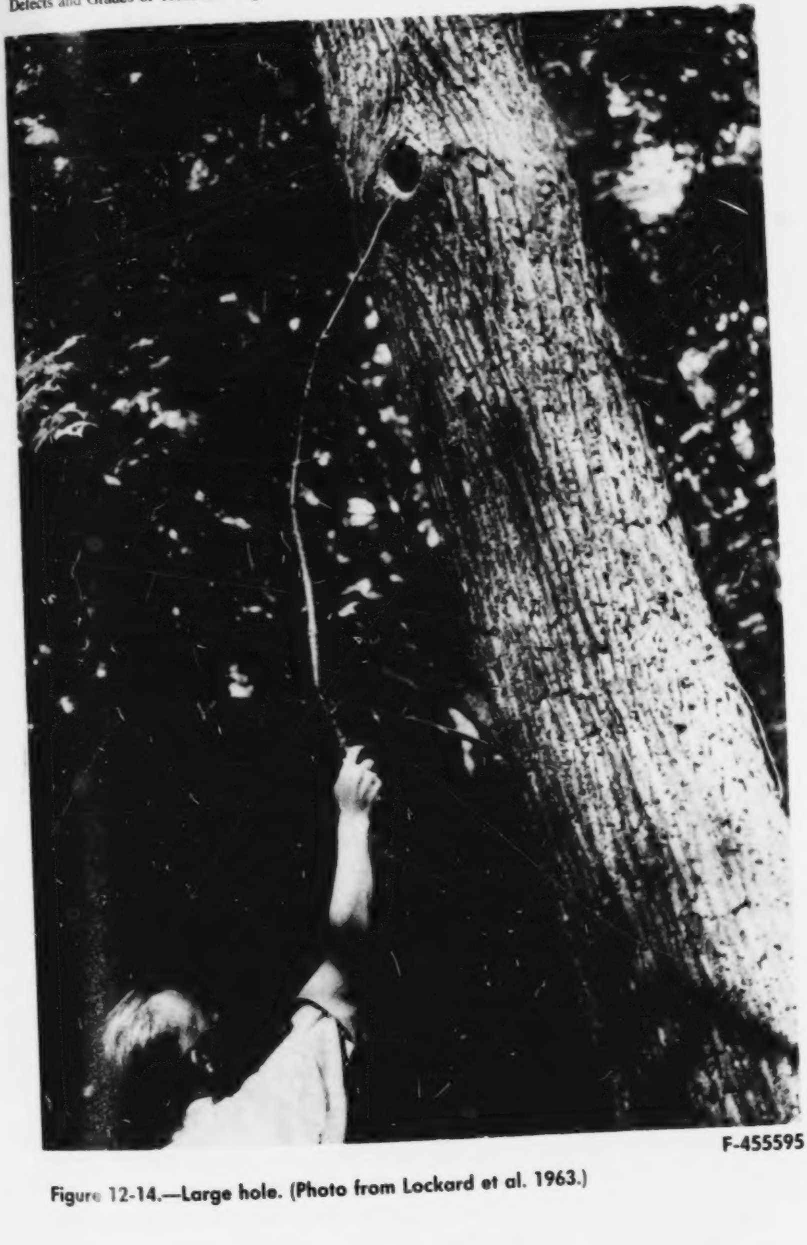

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Figure 12-14.—Large hole. (Photo from Lockard et al. 1963.)

Medium holes.—Medium holes, found in all species, are unoccluded openings, 3/16- to 1/2-inch in diameter through the bark which may or may not continue into the wood. They include entrance and emergence holes of insects (fig. 11-25 through 11-31), bark scarrer holes, tap and increment borer holes, and openings made by sapsuckers. Recent or fresh bark scarrer attacks appear as open holes about 1/4-inch or less in diameter. They can be identified by their round irregular outline and lack of penetration into the wood. Work of boring insects and bark scarrers may be indicated by a frothy, dirty-brown exudation. Sapsucker bird pecks, most often found in the hickories, elms, sweetgum, yellow-poplar, and water oak, are usually found in rows or bands (fig. 12-15), although occasionally an entire log may be freckled with them.

Except for extreme concentrations of larvae (grub) holes or associated carpenter ant work, medium holes can be disregarded in **construction** and **local use logs.** In **factory logs** they may be extremely important defects, but significance varies with origin, age, or concentration.

Larvae and borer holes (figs. 11-25 through 11-31), increment borer holes, and tap holes are definitely grading defects in **factory logs** for the hole or channel in the lumber limits length of cuttings. Carpenter ants sometimes enlarge these openings, increasing the degrading effect.

Increment borer holes are generally accompanied by severe stain.

Bark scarrer holes, if definitely identifiable, may be disregarded in all three classes of logs because the holes are inherently superficial, and often actually not in the wood at all. Fresh holes show exudations and stained bark. Caution is necessary because where holes are present earlier attacks are very likely to have occurred.

Significance of sapsucker damage depends primarily upon age and concentration. Fresh or light bird peck (fig. 12-15 left) may be disregarded in all types of logs. Test for freshness is lack of associated similar holes that are occluded (filled with callus tissue) after injury to the cambium. Measure of lightness is four pecks per square foot. There are two cautions in connection with light and fresh bird peck. One is that trees so damaged have generally been subject to previous and often repeated attack, and in such cases will have occluded holes. A second caution relates to the hickories; here even light bird peck often results in circular columns of purple stain running for considerable distances down the tree. This stain constitutes a degrading defect on handle stock. Bird peck in hickory lumber is limited in size and amount in Firsts and Seconds and No. 1 Common, but not in other lumber grades. The degree of bird peck is not the test for degradation. The test is occlusion.

Heavy bird peck (fig. 12-15 right) may be older and usually is accompanied by occlusions. The effects extend into the wood in the form of bark flecks or callus pockets. Thus, the chances are good that in most species heavy bird peck is a log grade defect in **factory logs** (fig. 12-15 bottom), but not in **construction** and **local use logs**. In yellow-poplar, however, especially on good sites, bird peck is not a degrader even though occluded.

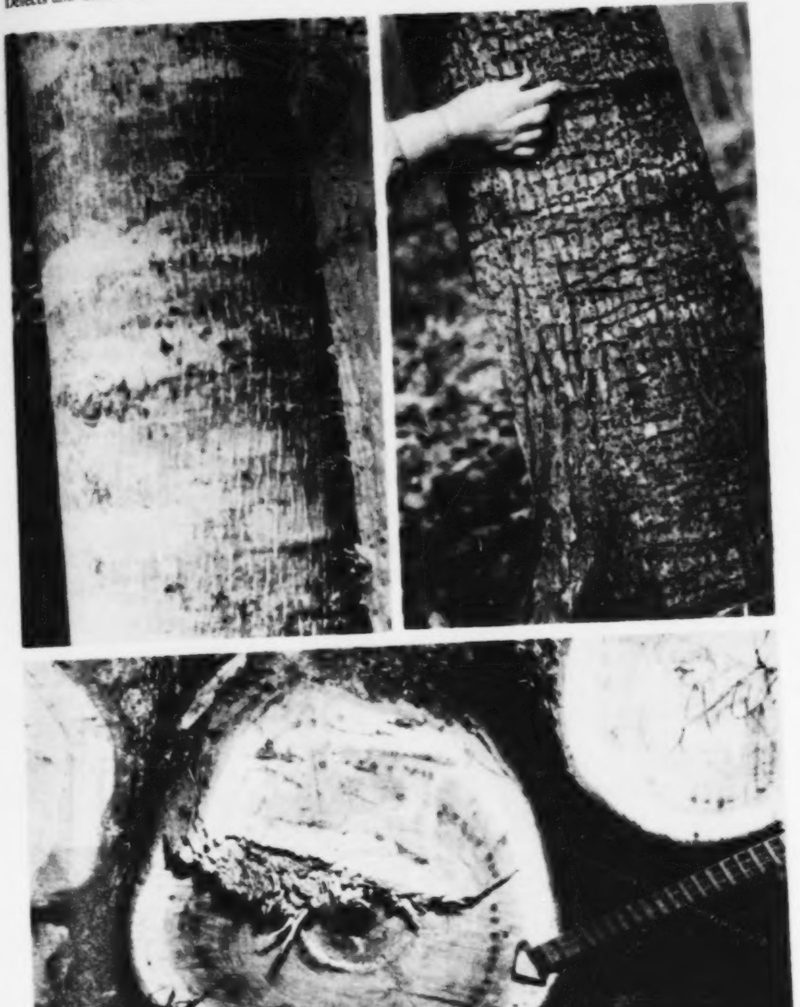

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Figure 12-15.—Bird peck. (Left) Light. (Right) Heavy. (Bottom) End view of hickory log showing stain caused by bird peck. (Photos from Lockard et al. 1963.)

Small holes.—**Small holes**, found in all species, are unoccluded openings less than 3/16-inch in diameter leading into the wood. They are made by several genera of beetles and their larvae. Oak timberworms (fig. 11-25) prefer oak species. Columbian timber beetles (fig. 11-26AB) extensively attack red maple and post oak, and, to a lesser extent, yellow-poplar, and elms. Ambrosia beetles (fig. 11-32) attack oaks, hickories, ashes, sweetgum, and hackberry. Hickories are particularly susceptible to attack by the false powder post beetle (fig. 11-33).

Small holes on the surface are often accompanied by other features, such as wounds or rot which may or may not be log grade defects. In **factory** logs the usual effect of small holes is to increase the already defective area containing the wound or rot. Even if not otherwise defective, the area in which the insects work is definitely a degraded area. Small holes may be disregarded in **construction logs** and in **local use logs**.

Log knots.—**Log knots**, common to all species, are cut or broken off limbs or sprout branches, green or dead, protruding, flush, or depressed, but with exposed sound or rotten wood (fig. 12-16). If the exposed wood is sound, the log knot is **sound**; if rotten, it is **unsound**. Knot frequency depends on species growth habit (figs. 3-33 through 3-58). In yellow-poplar, black tupelo, and the ashes, for example, occurrence is conspicuously limited. Scarlet oak and (on poor sites) black oak are conspicuously knotty.

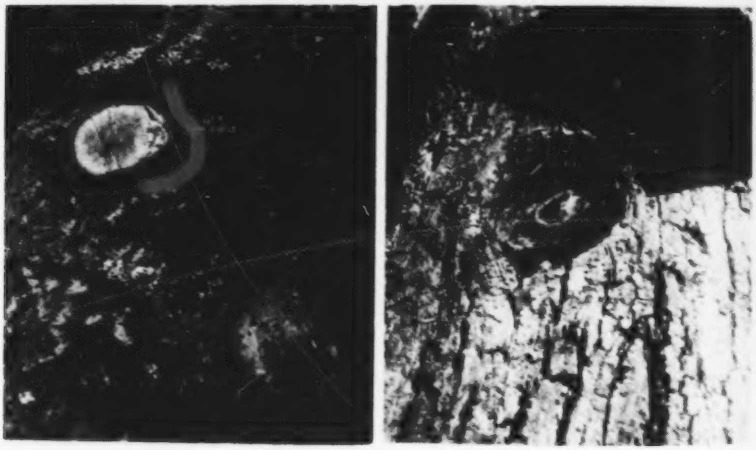

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Figure 12-16.—Log knots. (Left) Sound. (Right) Unsound. (Photos from Lockard et al. 1963.)

A log knot on the surface of the log or a branch on a tree represents a knot in the underlying wood.

In factory lumber the degrading effects of knots are determined by their distribution (which affects the yield of clear cuttings) rather than their size, character, or condition. Obviously, large knots will limit cuttings more than small knots, but a knot in lumber, no matter how small, will limit a cutting under standard hardwood lumber grades. Thus, any log knot is a degrader in **factory logs**. Even "surface" log knots, arising from epicormic or sprout limbs, cannot be discounted. Although a particular log knot of this origin may taper out at a shallow depth, it generally indicates successive layers of lumber knots for an indefinite depth into the wood (fig. 12-10).

In **construction logs** the degrading effect of a log knot depends upon its effect on timber strength. If the underlying lumber knot is larger than one-fourth of the face of the largest included timber (measured on the small end of the log), or if it is very rotten, it is definitely a defect; smaller sound knots do not degrade the log. Guides to the breaking point between the two conditions are as follows: a sound log knot is a defect in a construction log if the diamater of the log knot collar at the point of occurrence is greater than one-third the diameter of the log at that point. Log knots from epicormic branches, if absolutely identified as such, are not defects unless one-half the log diameter at the point of occurrence because they taper so rapidly.

Sound log knots smaller than one-third to one-half of the diamter are log grade defects if they occur in whorls equalling the effect of a larger degrading log knot.

Unsound log knots are judged by the same rule as sound ones, so far as size is concerned, but the rot cannot extend more than 3 inches into the included timber. In practice this means that an unsound log knot of acceptable size is a degrader if the rot extends into the log for a distance exceeding one-fifth of the log diameter.

In **local use logs** the only limitation on knots is that they must not extend across individual pieces of lumber. A good rule is that a log knot is a grading defect if the collar diameter exceeds one-half the diameter of the log at point of occurrence or if the aggregate of a whorl of smaller log knots is of equal size. Other log knots, even if unsound, may be disregarded.

Limbs.—A **limb** is a branch or subdivision of the stem or an outgrowth from the stem (fig. 12-17). It may have been one of the original branches, starting at the pith of the main stem, or it may have started later from dormant buds at varying distances from the pith. These epicormic limbs may be identified by their tendency to grow almost vertically parallel to the main tree stem, and often by an abrupt increase in diameter at the base. Their bark retains a smooth or juvenile appearance to a much larger size than that of a primary limb.

Limbiness varies with growth or development habit of each species (fig. 3-33 through 3-58). It also varies with conditions of growth such as spacing and site, age and size, competitive position, and health or vigor. Species generally most free from limbs are yellow-poplar, cottonwood (*Populus deltoides* Bartr. ex Marsh.) and the ashes, tupelos, and basswoods (*Tilia* sp.) Oaks—particularly black oak on poor sites, scarlet oak, pin oak, and sometimes water oak—are very limby.

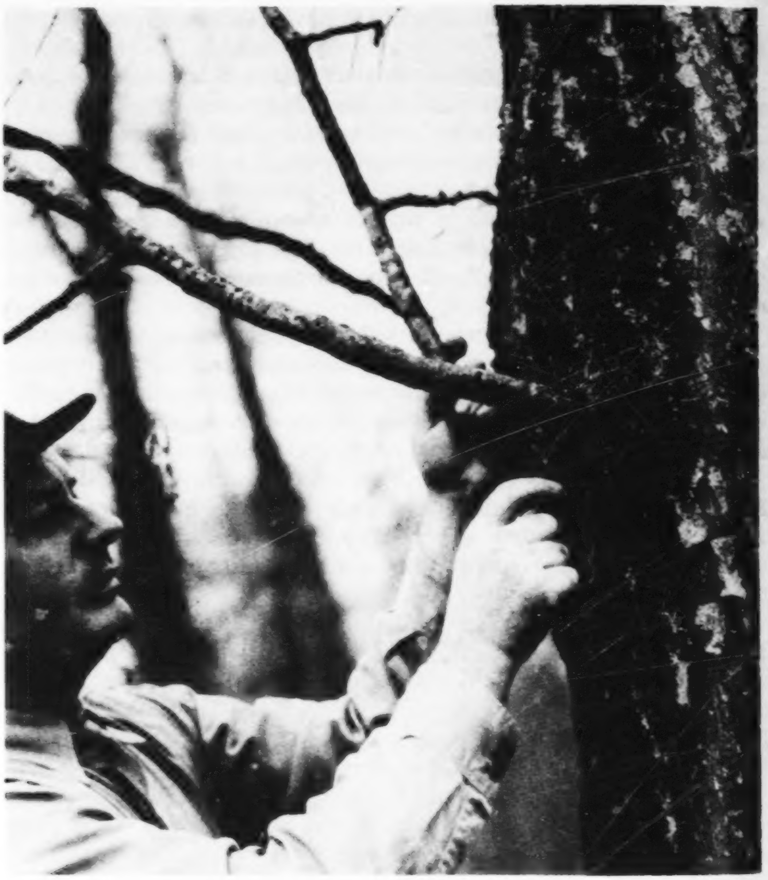

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Figure 12-17.—Adventitious limbs. (Photo from Lockard et al. 1963.)

Limbs are generally associated with sound knots in the sawed product. Since they degrade factory lumber regardless of size, condition, and character, they are log grade defects in **factory logs.** In **construction logs** and **local use logs** the same rules apply that relate to log knots; namely, there is a size limitation. If the limbs are above the size limitation or if smaller and arranged in whorls, they are defects which may prevent a log otherwise qualified from being put in one of these two classes. Otherwise, they may be disregarded.

Seams.—Seams, found in all species but common in the oaks, ashes, maples, elms, *Populus* sp., *Fagus* sp., and honeylocust (*Gleditsia triacanthos* L.), are longitudinal radial separations of the fibers in a log or tree, either open or overgrown with callus tissue (fig. 12-18). If the seam is overgrown, bark is usually encased. Seams are generally caused by stresses due to wind, lightning, or frost, especially in trees with cross or spiral grain, or which are buttressed or leaning.

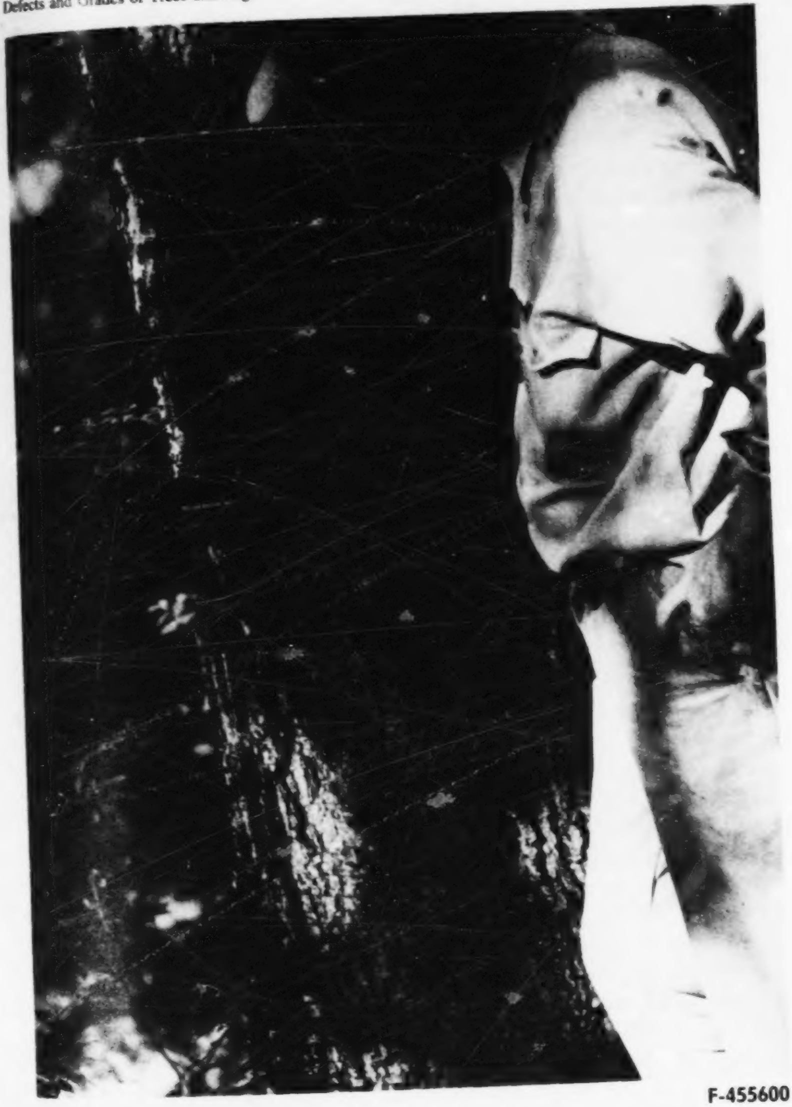

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Figure 12-18.—Seam. (Photo from Lockard et al. 1963.)

The significance of seams depends upon their depth. Often rot is associated with a seam; if so, consideration must be given not only to the seam but to the extent of the rot. In **factory logs**, if a seam together with any associated rot extends into the log for less than one-fifth of the log diameter, it can be disregarded as a degrader. If it goes deeper and is crooked, even though scale is reduced to allow for loss of lumber, it is still a degrader in that it stops cuttings. Straight seams can sometimes be located in the dividing line between two faces to minimize degrade. In **construction logs** a seam can be disregarded if it enters the largest included timber (as measured on the small end of the log) only slightly, say 1/2-inch. If a sound or unsound seam enters the timber deeply, however, it must be classed as a log grade defect which will eliminate the log from this class of use. In **local use logs** most seams can be disregarded.

Split.—A **split** is a longitudinal separation of fibers extending deeply into the milling frustum of a factory log or into the included tie or timber of a log designated for construction use (fig. 12-19). While generally caused by operational accident or carelessness (fig. 12-3), splits sometimes result from the release of internal stresses when the tree is felled; such splits are usually called **checks**.

The hickories, and the pecans (especially *Carya aquatica* (Michx. f.) Nutt.), are likely to split at any time because of release of internal stresses after cutting. Ash, *Salix* sp., cottonwood (*Populus deltoides* Bartr. ex Marsh.), and overcup oak (*Quercus lyrata* Walt.) often split badly if cut at the peak of the growing season.

Superficial splits can be disregarded. In **factory logs** splits extending more than one-fifth the diameter into the log are degraders even though the portion of the lumber ruined be scaled out. In **construction logs** end splits which do not extend lengthwise more than 5 inches beyond the trimming allowance can be disregarded. Other splits must be considered as degraders. In **local use logs** splits can be disregarded.

Surface rise.—A **surface rise** is a notable, smooth undulation in the surface of the log or tree bole which gradually tapers back in all directions to the normal contour (fig. 12-20). Because of the nature of this abnormality there can be no mimimum height specification other than the ability of the eye to notice it. When the taper is steeper than 1 in 6, the abnormality is classed as a bump (fig. 12-8). A surface rise is usually the effect of a small limb stub, a cluster of adventitious buds, or a deeply buried knot or wound. Sometimes a rise reflects an earlier crook in the stem.

Since the lumber defects underlying surface rises are so deeply buried that their degrading influence cannot be assessed accurately, they can be disregarded as grade defects in logs of all types. It is important to differentiate between a surface rise and a bump because the latter is an important degrader. This is particularly hard to do when skidding has rubbed off some of the bark.

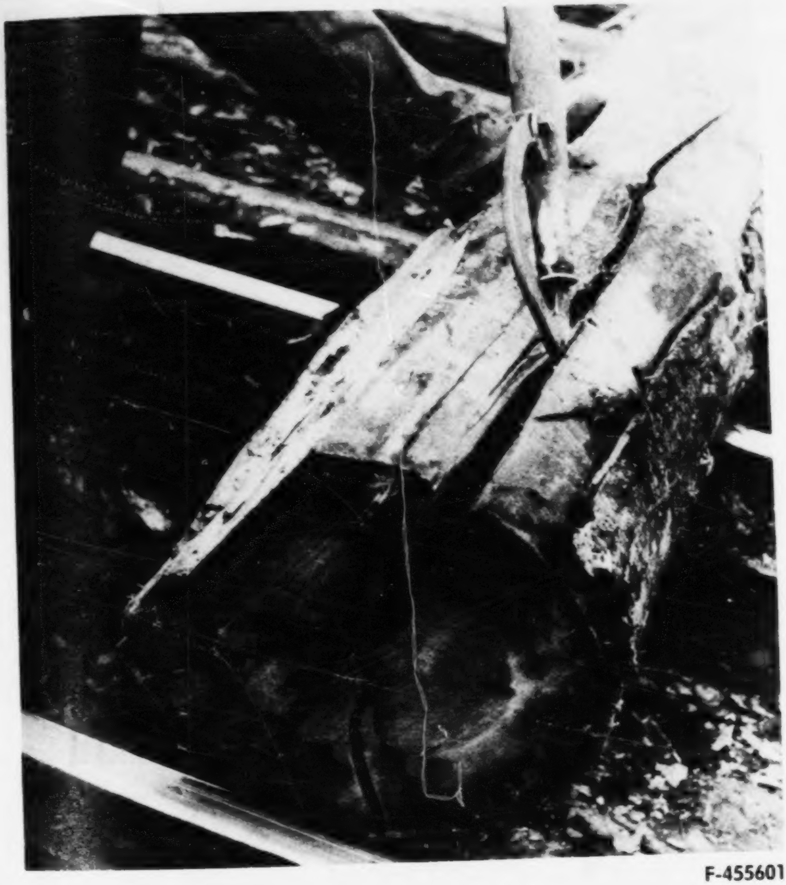

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Figure 12-19.—Split. (Photo from Lockard et al. 1963.)

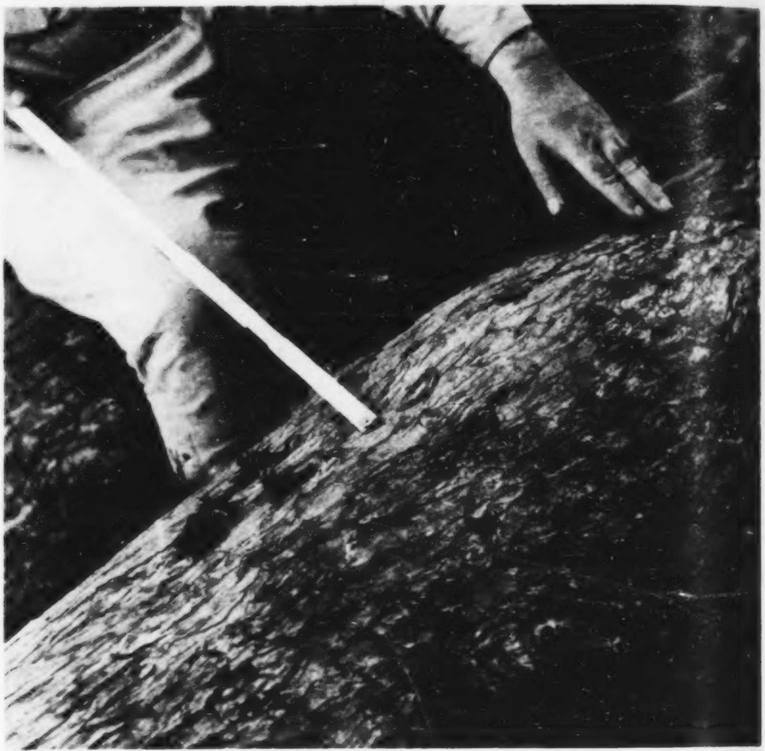

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Figure 12-20.—Surface rise. (Photo from Lockard et al. 1963.)

Wounds.—**Wounds** are openings in the bark that expose sapwood and sometimes heartwood (fig. 12-21). A **new wound** is a surface injury exposing sound sapwood. An **old wound** is a similar injury, completely open or only partially healed over, identified by unsound sapwood, local hollow, much callus tissue, insect damage, and often by stained or actually rotten heartwood.

In a new wound deterioration is usually not serious, for any insect damage or stain will be quite superficial. For all types of logs, most new wounds can be disregarded as log grade defects. However, with some species, e.g., sweetgum, hickories, hackberry, *Salix* sp., *Magnolia* sp., and *Tilia* sp., deterioration from wounds is often rapid.

The seriousness of an old wound varies considerably with locality and with species. In some species exposed heartwood may completely heal over before serious injury occurs. Since old wounds are usually associated with stain, rot, and insect damage, however, the affected area is a grading defect in both **factory logs** and **construction logs**, except in the rare cases where it is superficial. In the factory logs, even if scale deduction is made to cover the area involved in worthless wood, the area will stop a cutting. Old wounds can be disregarded in **local-use logs**.

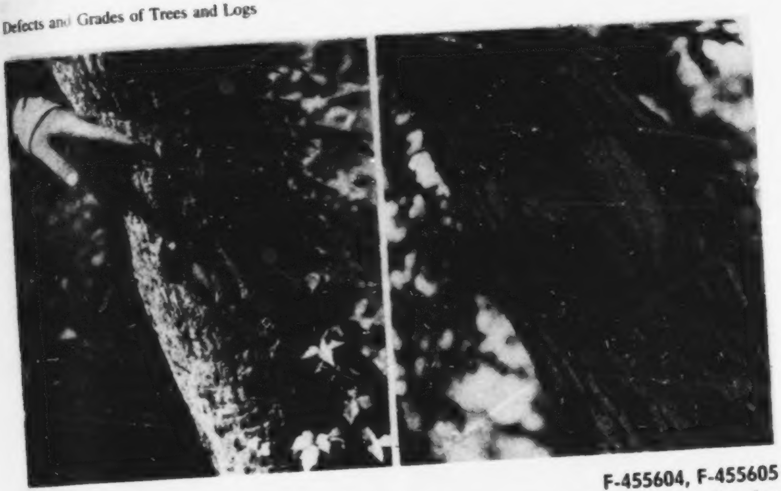

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Figure 12-21.—Wounds. (Left) New wound. (Right) Old wound. (Photos from Lockard et al. 1963.)

OVERGROWTHS—CLUES TO INTERIOR DEFECTS

Many log surface abnormalities appear as breaks in the normal bark pattern of the tree. Log knots (resulting from broken or cut branches), mechanical wounds (as from ax blaze or logging), and discrete holes such as those made by sapsuckers or insects are common causes of this type of abnormality. As the tree develops, they are covered over by callus tissue and finally engulfed in the wood. As the years pass, the bark reforms and the presence of a blemish in the wood may be shown only by a deformation of the general normal surface contour. A bump (fig. 12-8) is an extreme example of this.

Deeply buried smaller features may leave no external evidence. For many years, however, most features—until they become so deeply buried in the heart as to lose significance as product defects in the quality zone—leave either a definite structure of callus, or an identifiable break in the normal bark pattern. Such features are classed as **overgrowths**. They actually are phases of other log abnormalities previously described. Yet, because many of them are inconspicuous and easily overlooked, and because they are the least understood of all the hardwood log surface abnormalities, they are considered together for emphasis.

A recently overgrown log knot is an example of a very conspicuous and easy-to-recognize feature in this class. Less easily recognized are evidences of old insect work. Such damage may be so hidden that the only indication of its presence is a general appearance of the bark, which to the trained eye signifies a need for close search for individual overgrowths. The importance of overgrowths in evaluations of hardwood factory lumber logs in particular cannot be overemphasized. Appraisal on the basis of all other log grade defects would, in most situations, be fallacious if overgrowths were not consistently recognized and given full weight as product defect indicators (fig. 12-22A through L).

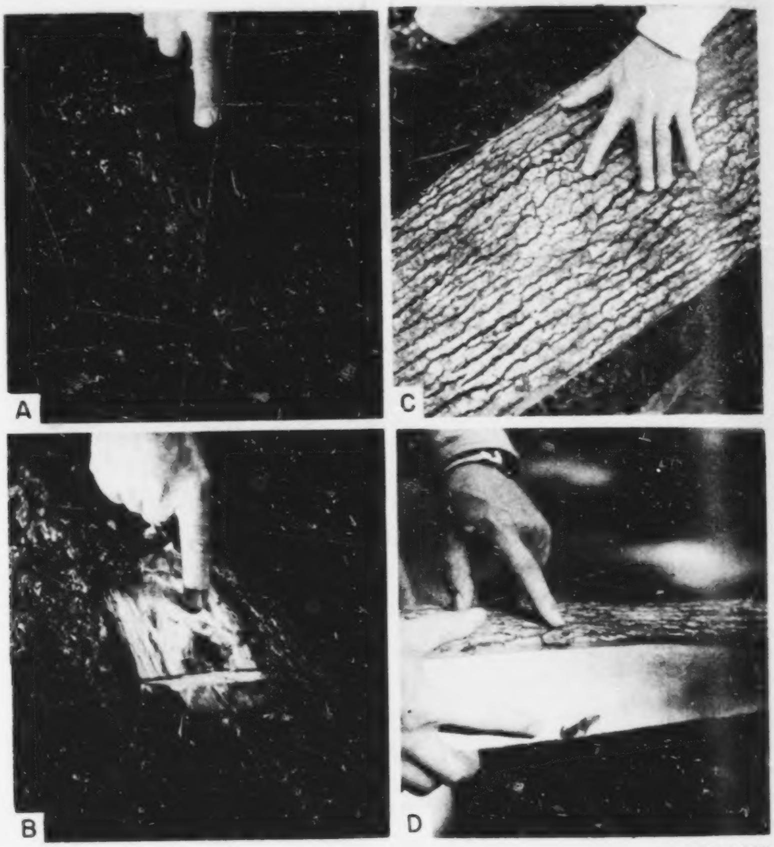

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Figure 12-22ABCD.—Overgrowths. (A,B) Overgrowth in water oak caused by small log knot recently overgrown. (C,D) Overgrowth in black tupelo due to deeply buried log knot. (Photos from Lockard et al. 1963.)

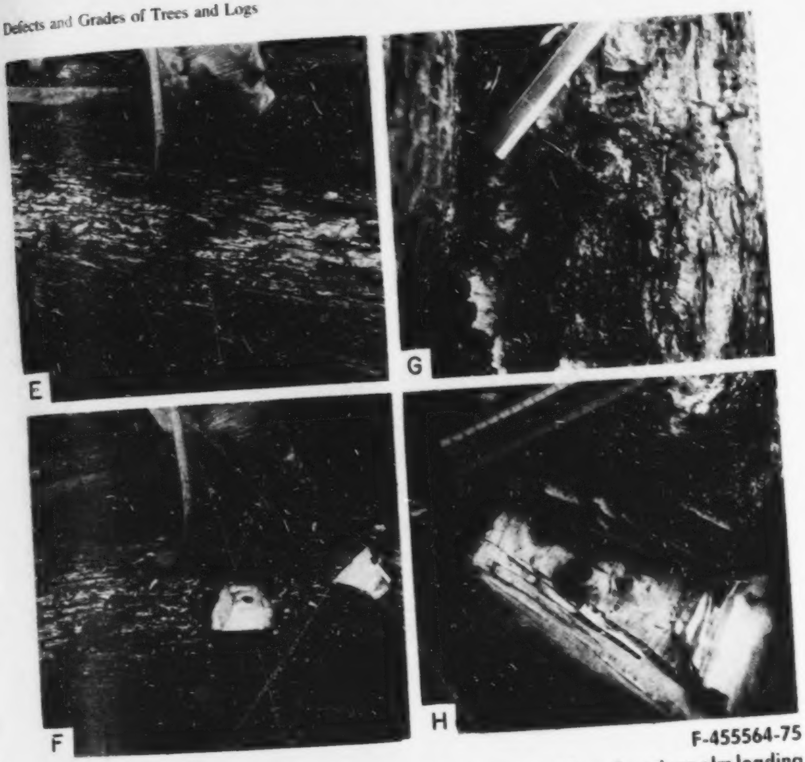

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Figure 12-22EFGH.—Overgrowths. (E,F) Small epicormic limb on American elm leading to lumber knots. (G,H) Overgrown epicormic buds surrounding an epicormic branch. (Photos from Lockard et al. 1963.)

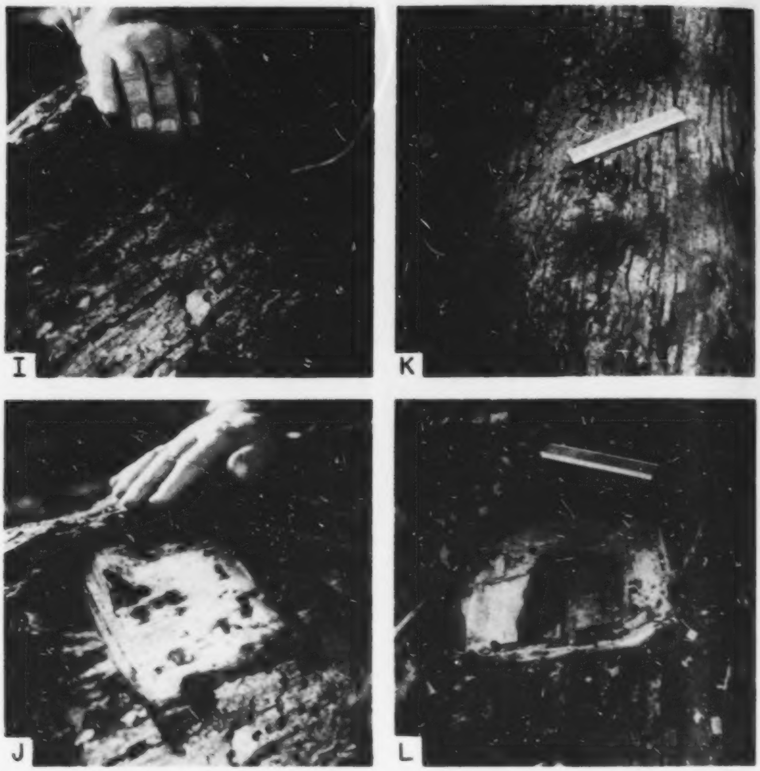

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Figure 12-22IJKL. Overgrowths. (I,J) Bird peck in white oak. (K,L) Larvae-caused overgrowth in overcup oak. (Photos from Lockard et al. 1963.)

Overgrowths may be grouped into four relatively distinct classes, three reflecting origin (knots and associated bark pockets, insect work, sapsucker damage), and a fourth (bark distortions) of uncertain origin.

Overgrowths related to knots and associated bark pockets.—The most obvious overgrowths are those indicating overgrown or buried log knots and associated ingrown bark (fig. 12-23). Where single log knots are involved, the overgrowth in early stages of development takes the form of the underlying log grade defect. Whether the log knot is covered over with callus tissue or there is a circular excrescence of callus tissue around it, there still is a separation between this tissue and the normal bark. The log knot is gradually engulfed as time goes on, but for many years definite swirls or lines form on the bark, making a characteristic pattern of roughly concentric circles most distinct at the base.

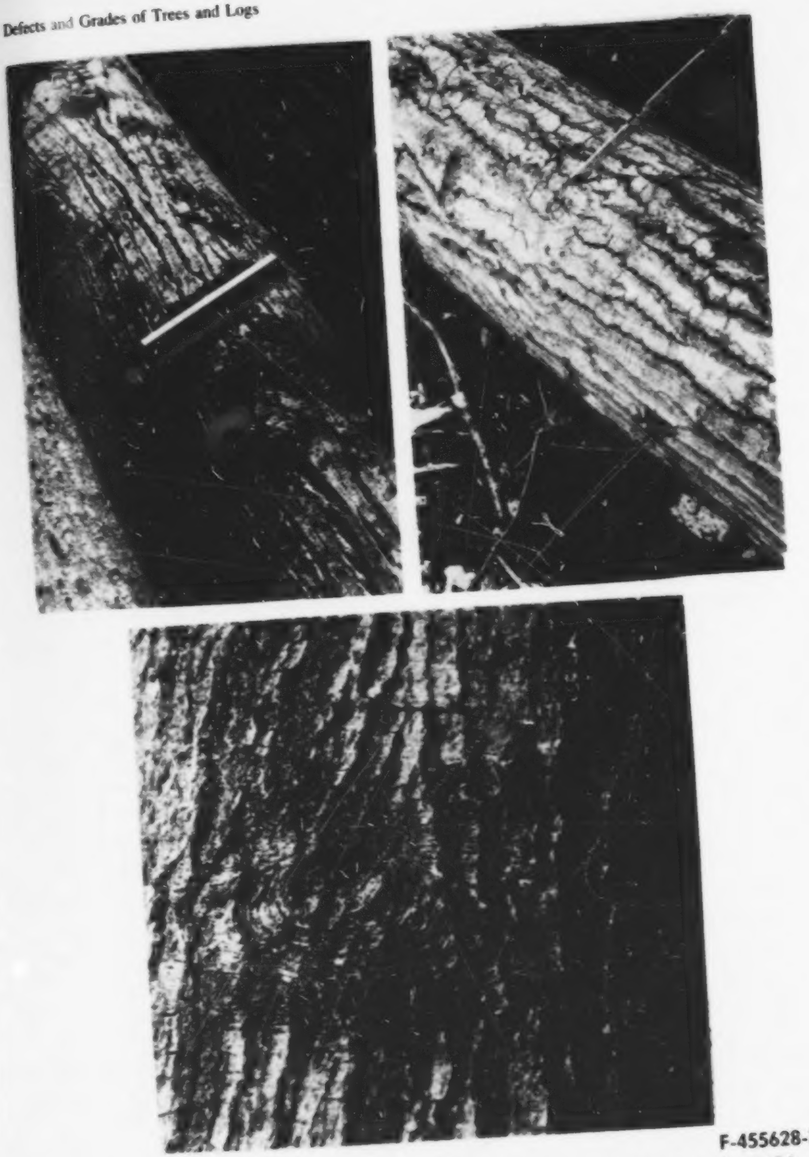

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Figure 12-23.—Overgrowths caused by knots. (Photos from Lockard et al. 1963.)

These patterns, which are so definite that there can be no mistaking their cause, persist until the log knot becomes so deeply buried that it will not be found in the quality zone. From this stage on the characteristic bark signs gradually disappear, and the deeply buried knot is evidenced by a bark distortion which may be merely a faint break in the normal bark pattern. When clusters of small log knots (generally from epicormic growth) with associated bark pockets are involved, a small rise or slight bump may be formed during the early stages of overgrowth. The bump or rise resembles that covering a large single log knot. These small bumps sometimes run together to form a sort of rosette. The final stages are similar to those of the single log knot, except that the bark distortion is apt to be wider and more irregular.

There is no relation between such overgrown log knots and species except that some species are limbier than others. This class of defect is often overlooked in well-stocked stands of rapidly developing, well-cleaned second growth timber and especially in upper logs. Recognizing overgrowths in such stands is particularly important because, although general appearance may be one of clearness of bole, the underlying knot is just beneath the slab.

Each log-knot-caused overgrowth indicates an imperfection (knot) in the quality zone of the underlying wood. In **factory logs** each is a log grade defect. In **construction logs** the overgrowths can be disregarded except when they are of abnormally large size or, if small, when whorled. Overgrowths of this class can be disregarded in **local use logs**.

Overgrowths related to insect attack.—Common and extremely important distinctive bark irregularities are those covering holes caused by the work of such insects as wood borers (fig. 12-24) and bark scarrers (fig. 12-25). Bark scarrer work by round-headed borers or carpenter worms that mine under the bark results in irregularly puckered scars covering the entrance hole and surrounding area of bark destroyed by the feeding larvae. The size of overgrowth varies from 2 inches to 3 by 5 inches in dimension. Roundheaded borer exit holes will be covered by a sharp pucker consisting of a pitted core with callus tissue and distorted bark extending over an area 3/4-inch to 2 inches in diameter. Generally, borer-caused overgrowths in bottomlands involve carpenter worm work (fig. 11-31), while in uplands they involve roundheaded borer work (figs. 11-27 and 11-28).

The covering of bark scarrer work usually shows as a vertical slit from 3/4 to 3 inches long with callus area on both sides. The total maximum affected area is typically about 2½ inches wide and 6 inches long. The most extreme development of this type often looks like a small healed blaze wound. In late stages projecting scales of normal bark from surrounding areas may hide these distortions. These concealing bark scales, particularly in mature trees, may contain holes 1/8- to 1/4-inch in diameter, or exhibit numerous transverse breaks, cracks, or ridges which indicate that overgrowths are present.

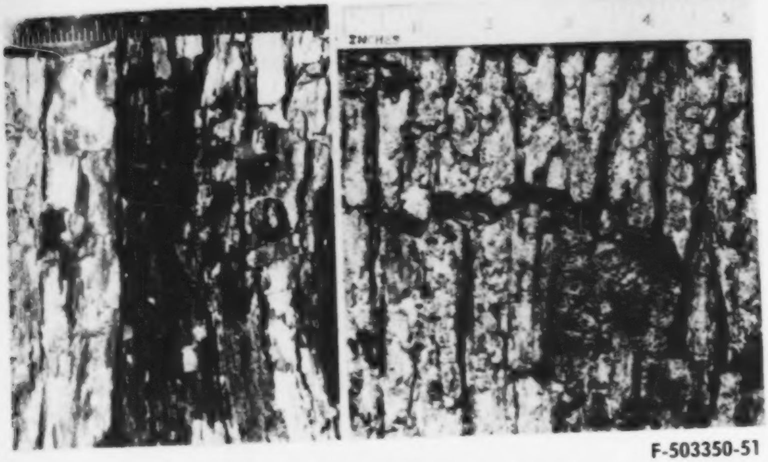

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Figure 12-24.—Overgrowths caused by borers. (Left) Roundheaded borer exists. (Right) Carpenter worm entrance and exit, or borer entrance. (Photos from Lockard et al. 1963.)

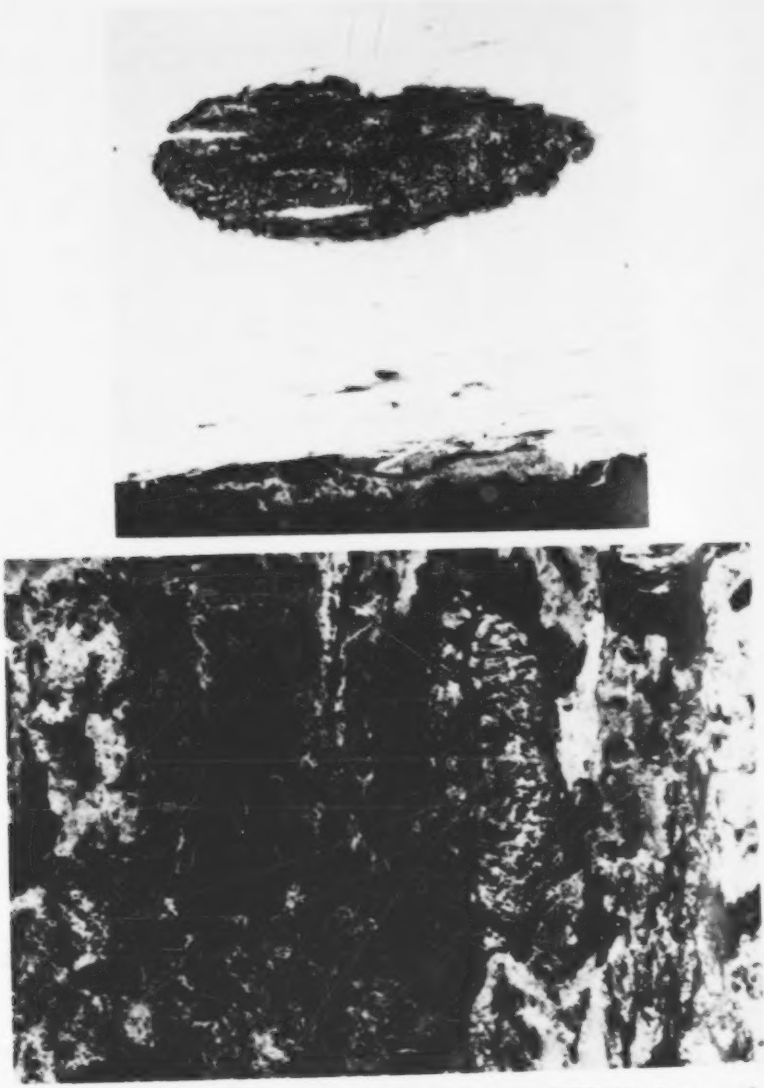

Figure 12-25.—Overgrowths caused by bark scarrers. (Top) Bark pocket at wood surface, but no hole. (Bottom) Log surface. (Photos from Lockard et al. 1963.)

Another type of bark scarrer overgrowth (fig. 12-26) closely resembles the overgrowth of the roundheaded borer exit hole, making a precise distinction between the two difficult. Moreover, in some situations this general type of scarrer injury causes numerous breaks in the cambium, many of which are little larger than coarse bird peck and which result in finely puckered overgrowths that are hardly as conspicuous as individual coarse bird pecks. The usual overgrowth of this sort is slightly larger, however, than that associated with roundheaded borer exit holes and is generally less regular and clean cut with more radiating lines in the pucker.

This general class of insect-caused overgrowths is definitely related to tree species, and within species to site and stand history. Although widespread over the entire East, it is most prevalent in the South, especially in the valleys of the lower Mississippi River system and the lower Coastal Plains. Occurrence is closely related to sites, being affected not only by the sharp differences between the alluvial and upland situations, but also by the widely varying growth conditions in the lowlands.

The oaks and some of the hickories are most susceptible to attack. Of the hickories, sweet pecan (*Carya illinoensis* (Wangenh.) K. Koch) is an exception and is almost entirely free of insect attack. On other hickories occurrence is likely to be most important on poor, dry sites, whether lowland or upland.

In the oaks three groupings can be made. Usually free from insect-caused overgrowths are northern red, Shumard, and cherrybark oaks, as well as swamp chestnut oak (*Quercus michauxii* Nutt.), Delta post oak (*Q. stellata* var. *paludosa* Sarg.), and swamp white oak (*Q. bicolor* Willd.). Damage to cherrybark and swamp chestnut oak is mainly confined to bark scarrer work, which is occasionally serious in overmature trees on poor sites.

Rather generally infested are laurel, scarlet, blackjack and chestnut oaks, and also overcup oak (*Q. lyrata* Walt.) and chinkapin oak (*Q. muehlenbergii* Engelm.).[3]

In most other oaks the degree of damage is dependent upon the specific nature of the site. Among white, black, southern red, and post oaks—also shingle oak (*Q. imbricaria* Michx.), insect-caused overgrowths are most common in timber from dry, poor sites, such as exposed high slopes, ridge tops, and most Coastal Plain pine sites. On normally good hardwood sites insect damage to those species is usually slight or absent. White oak, especially, is quite free from insect damage on good hardwood sites, but is usually badly damaged on pine sites of the lower Coastal Plain.

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[3] For discussion of these relationships see Putnam et al. (1960).

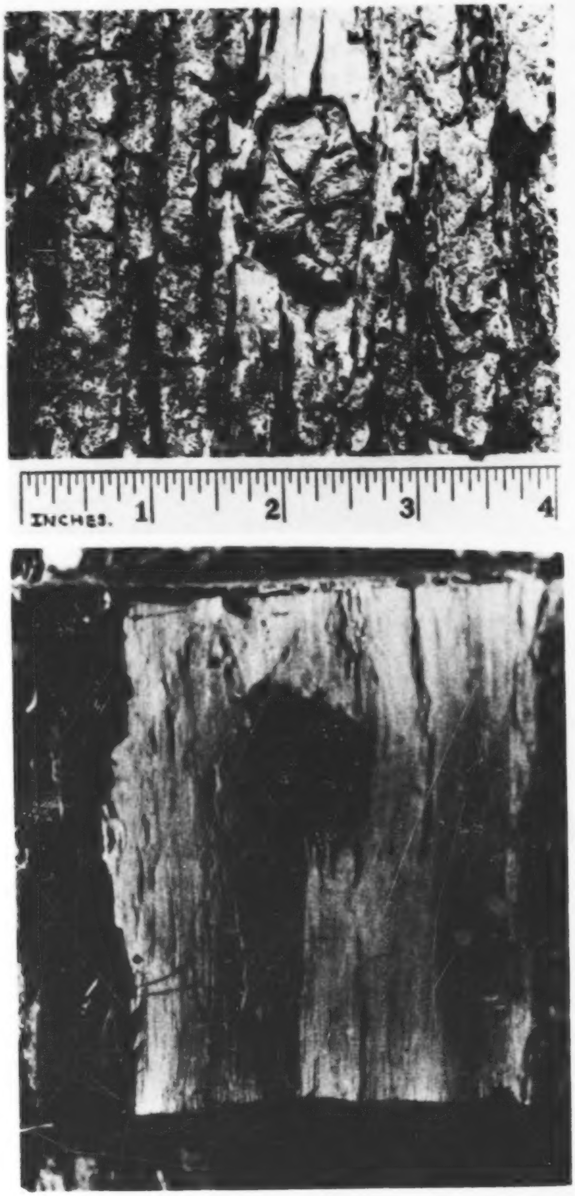

Figure 12-26.—Another type of bark scarrer overgrowth, easily confused with borer exits. (Top) Healed scar 1 by 1.6 inches. (Bottom) Surface of wood beneath scar shows ingrown bark but no penetration of wood. (Photos from Lockard et al. 1963.)

In a second subgroup—all typical flood plain oaks (Nuttall or *Q. nuttallii* Palmer, bur or *Q. macrocarpa* Michx., willow or *Q. phellos* L., pin or *Q. palustris* Muenchh., and water oaks)—overgrowth occurrence varies more widely than in the terrace and upland species. The timber is likely to be very defective when growing on hardpan flats on terraces, in back-water areas where inundation is prolonged, and where soil is tight clay, and on dry upland (non-alluvial) sites. Frequency of past fire injury may drastically affect occurrence of insect damage in these species. They are likely to be free of such defects only on the best flood plain sites.

In many other hardwood species insect-caused overgrowths may be found, particularly in trees on unfavorable sites. However, the definite relationships or the specific indicators found in the oaks are absent, except that green ash in poor, deep swamp sites may show serious borer infestation over wide areas. Insect-caused overgrowths are also likely to be important in extra large, overmature, and decadent sycamore (*Platanus occidentalis* L.) and cottonwood (*Populus deltoides* Bartr. ex Marsh.) on poor dry sites.

Susceptibility to insect damage of the pine-site oaks that are the subject of this text is summarized as follows (other oak species in parentheses):

Species practically free of damage
  cherrybark
  northern red
  Shumard
  (swamp chestnut)
  (Delta post)
  (swamp white)
Damage slight on good sites and heavy on poor ones, if burned, if overmature
  laurel
  (overcup)
Damage medium on good sites and heavy on poor ones, if burned, if overmature
  blackjack
  chestnut
  scarlet
  (chinkapin)
Damage slight on terraces or second bottoms and good upland sites; heavy on dry, sterile upland sites
  black
  post
  southern red
  white
  (shingle)
Damage slight on well-drained alluvial soils and good upland sites; heavy on hardpan flats, backwater areas with tight soils and prolonged inundation, and dry upland sites
  water
  (bur)
  (Nuttall, only found on alluvial sites)
  (pin)
  (willow)

Cherrybark and swamp chestnut oaks, if overmature or damaged, may be badly infested with bark scarrer on poorly drained sites.

Larvae- or borer-caused overgrowths cover channels in the wood and bark pockets at the points of entrance, emergence, or both. The holes indicated by this type of overgrowth are rarely under 1/4-inch in diameter and are often accompanied by rot and stain. In factory lumber each channel or hole in a board is a product defect, and in **factory logs**, therefore, each overgrowth is a log grade defect. In **construction logs**, unless the holes are very numerous (usually with other defects such as loose heart, shake, and rot), the holes and channels do not degrade the product and can be disregarded. They can also be disregarded in local use logs.

Bark scarrer overgrowths indicate bark pockets which degrade factory lumber, with the strong probability of additional similar lumber defects in different planes. Bark scarrer-caused overgrowths, therefore, are log grade defects in **factory logs** but may be disregarded in **construction logs** and **local** use **logs**. Since heavy bark scarrer work is commonly associated with check, shake, and incipient rot, the combination often makes the log worthless for any purpose, as is the case with larvae damage.

An overgrowth caused by horizontal bark scarrers (fig. 12-27), found in white oak everywhere in the Southern Coastal Plain, on all but the best hardwood sites, degrades **factory logs** of this species. The insect often produces a horizontal channel 1/8- to 1/4-inch in diameter across one-fourth of the tree circumference. The overgrowth is typically a narrow band of callus tissue from 3 to 10 inches long.

Overgrowths related to sapsucker work.—Species most susceptible to attack by sapsucker woodpeckers are hickories, elms, sweetgum, yellow-poplar, and white oak. The other oaks, maples, and birches are damaged moderately. Overgrowths that cover the peckholes of sapsuckers may be recognized by the conspicuous, horizontal row or belt pattern of occluded holes about 1/4-inch in diameter (fig. 12-28). Occasionally the entire log is freckled with such bird peck. Where the holes are continuous, a horizontal crack often forms.

Overgrowths from sapsuckers indicate small holes or groups of holes filled with callus tissue. One attack would cause imperfections in only one plane, affecting only a few boards, but most affected trees have been damaged repeatedly over a number of years. The progress of occlusion and occurrence of horizontal cracks indicate how long ago the injury occurred. Wide variability makes the extent of damage difficult to predict. Except for very large butt logs, it is safe to assume that damage extends far into the tree and affects a large part of the volume. Thus, these overgrowths must be considered as log grade defects in **factory logs**. Usually the damage does not weaken large pieces of wood and, therefore, this type of overgrowth can be disregarded in **construction** logs and **local use logs.**

Overgrowths of uncertain origin.—Overgrowths of uncertain origin are called bark distortions. These are faint or indistinct but still discernible breaks in the normal pattern of the bark (fig. 12-29), exhibiting no characteristic formation by which the cause can be identified. They may result from the deep burying of any of the defects already discussed: insect damage, wounds, bird peck, or—most commonly—knots.

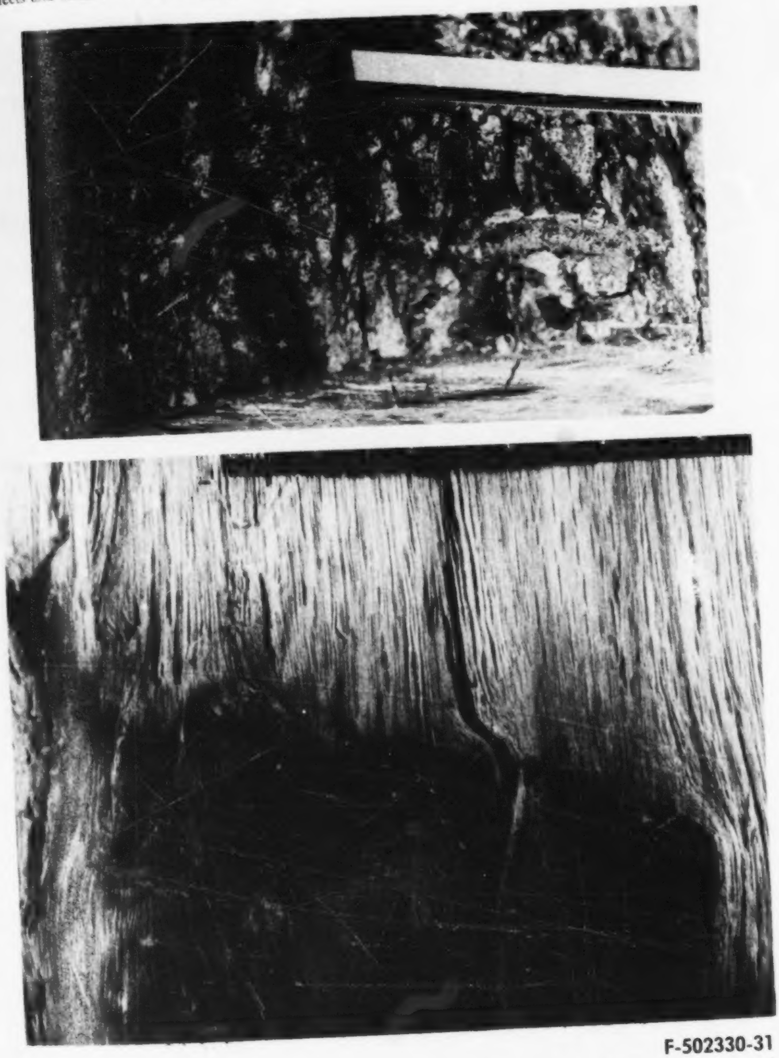

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Figure 12-27.—Effect of unknown trunk-boring insect in overcup oak. (Top) Horizontal bark scar. (Bottom) Typical gallery. A similar defect in white oak is distinctly finer, being only 1/8-inch or less in width. This defect seriously degrades most of the white oak in the Coastal Plains piney woods and is the principal cause of prevalent low quality in that area. (Photos from Lockard et al. 1963.)

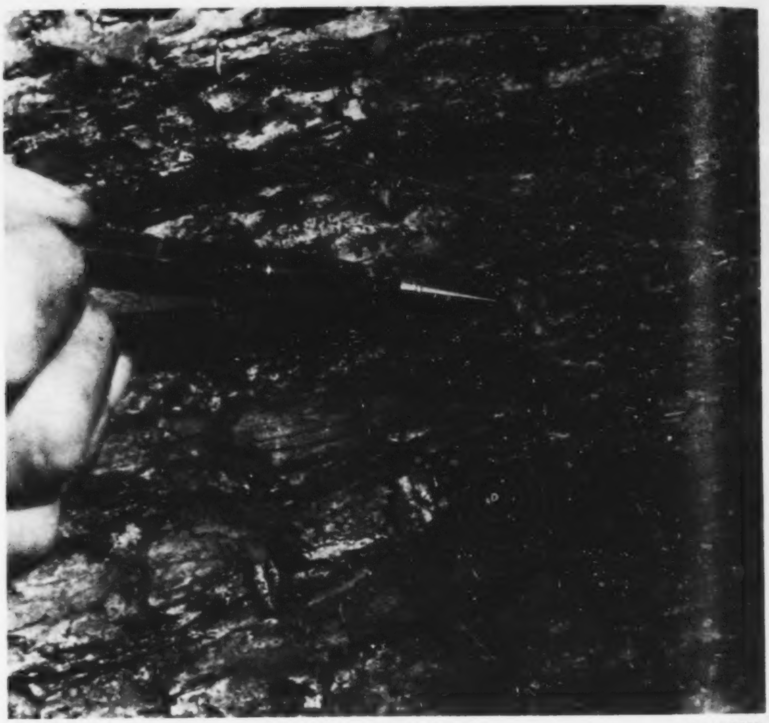

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Figure 12-28.—Overgrowths caused by sapsucker work. (Photo from Lockard et al. 1963.)

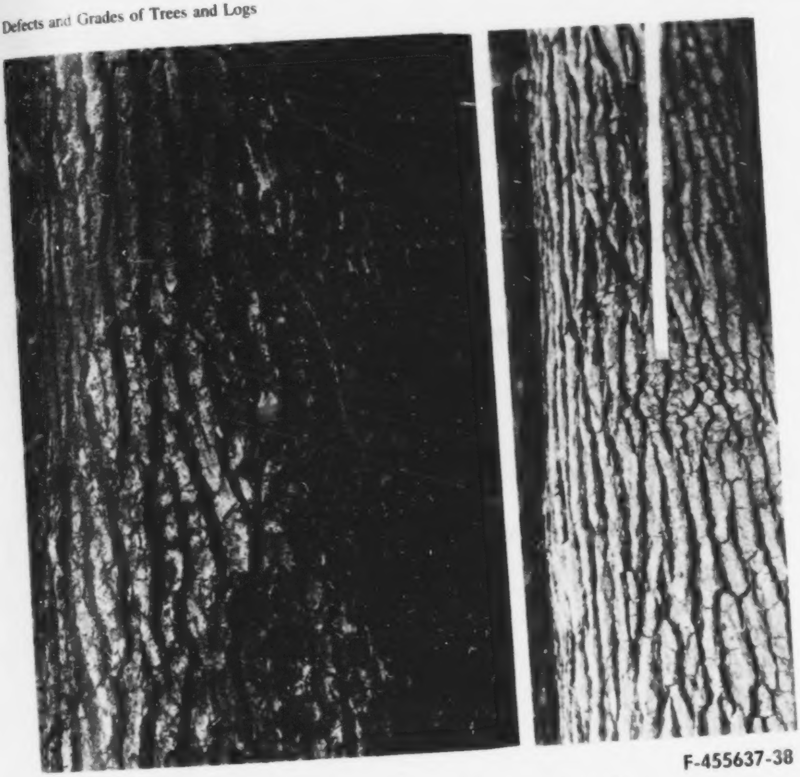

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Figure 12-29.—Bark distortions. (Photos from Lockard et al. 1963.)

Bark distortions (as defects) have the same relationship to species as do their causes. A smooth-bark tree, such as beech, carries the evidence of these deeply buried defects on the bole much more clearly than does a rough-bark tree like soft elm. Bark distortions are relatively prominent on young sweetgum, yellow-poplar, cottonwood, and second-growth red and water oaks.

Bark distortions reveal the presence of deeply buried blemishes. It is important to direct special attention to them because they are inconspicuous in their later stages and, consequently, easily overlooked. In all stages they can be disregarded as defects in **construction** and **local use logs**, but must be regarded as degraders in **factory logs** under 15 inches in diameter. In **large factory logs**, however, bark distortions are of such variable degrading effect that they can be disregarded.

LOG END ABNORMALITIES

The log abnormalities so far discussed have been those visible on the surface indicating imperfections in the wood. Sometimes the end of the log exposes what lies beneath defects such as bird peck, grub (larvae) work, advanced rot, knots, bark pockets, wounds, seams, flutes, and many other surface abnormalities. If surface indications are present, such "end abnormalities" are ignored, with one exception. This exception is made for grub channels, the radial or longitudinal burrows of wood-boring insects with definite and recognizable entrance and exit holes on the surface.

The log end may also reveal imperfections which normally have no surface indicators. These are the so-called "hidden" defects that demand local experience for their appraisal in standing timber.

Many of these end features are somewhat different from other product defects in that they are often admitted to a certain degree in the products, and in that their degrading effect is often based on concentration rather than presence alone. Sometimes their effect is covered by special grades which admit the blemish in the product, but which bring a reduced product price. Also, their location is important. Some which occur only in the heart center may be disregarded in one type of log; in another type of log the same imperfection in the same position will mean a drop in log class or require culling the log.

Many of these features are difficult to judge because they are found on one end of the log only, and the observer must use considerable judgment in determining how far into the log the blemish extends. Many are in the class of the scalable defects, and in judging their significance as a log grade defect, the relation to the particular product for which the log is best suited must be carefully considered.

Double pith.—When a tree bole forks and a log is cut just at the base of the fork, the end of the log will seem swollen; the top will have two separate pith centers, often separated by a bark pocket. This condition is called **double pith** (fig. 12-30).

Double pith leads to cross grain in sawn products, together with a split or potential split from the bark pocket. The general approximate effect is that of two large knots. In **factory logs** double pith is not a degrader; nevertheless, the related seam and any enclosed bark should be treated as in the case of fork (fig. 12-12). In **construction logs** double pith is a degrader. Double pith is not a degrader in **local use logs**. In standing timber double pith may be disregarded if the section including it can be cut out leaving logs meeting the minimum dimension requirements of the log class.

Grease spots.—**Grease spots** are limited, shadowy streaks with a dirty "greasy" look. They are sooty or brown in color and surround oval, frass-filled insect channels 1/16-inch in diameter (fig. 12-31).

Grease spots occur principally in overcup oak and locally in chestnut and white oaks. They are generally found in overcup oak in backwater flooded areas of the larger river bottoms and in the other species on poor, dry sites with a bad fire history.

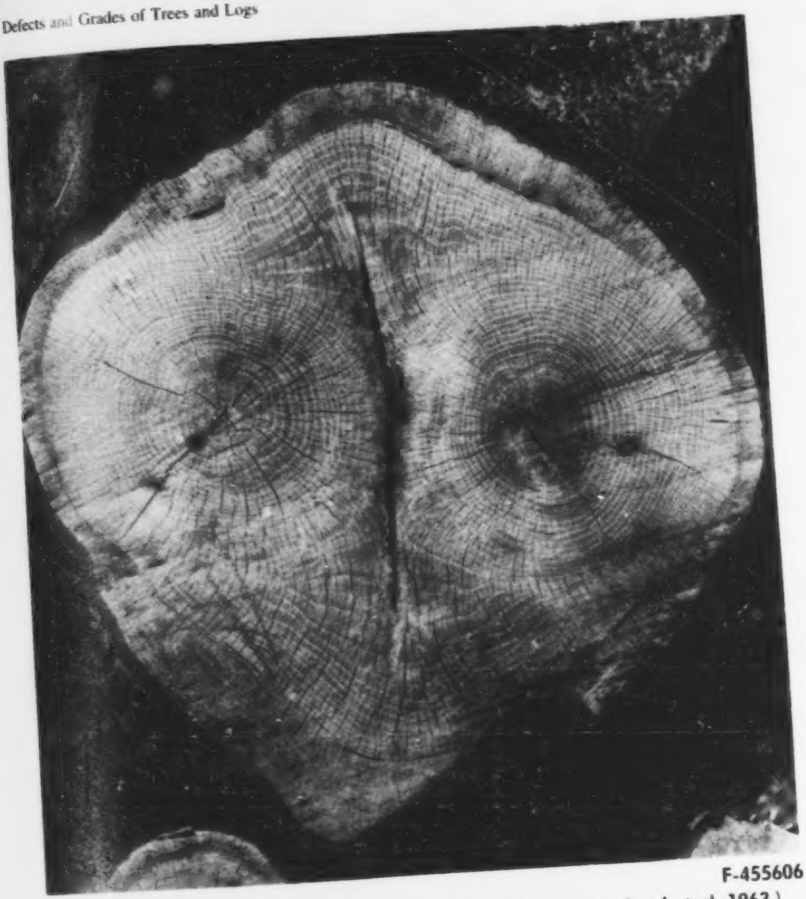

Figure 12-30.—Double pith. Note ingrown bark. (Photo from Lockard et al. 1963.)

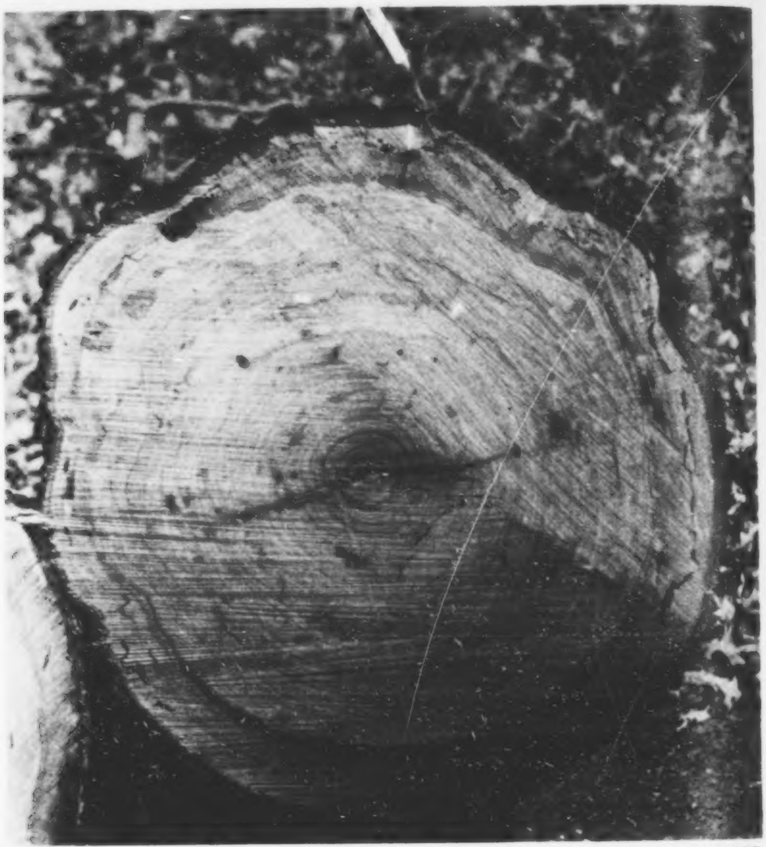

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Figure 12-31.—Grease spot. Cross section of 28-inch overcup oak log with signs of "grease spot" damage. Dark lines and spots indicated flatheaded borer (family *Buprestidae*) galleries and associated stained wood. All lumber from this log graded "sound wormy" from grease spot defects. (Photo from Lockard et al. 1963.)

In **factory logs** they are log grade defects if in the quality zone; in the other classes they can be disregarded.

Grub channels.—**Grub channels**, found in any species but most often in the oaks—particularly in water, overcup, and chestnut oaks, are round holes or irregular channels of varying length, from 3/8 to 1 inch in diamter (fig. 12-32). They are made by wood-consuming insect larvae hatched from eggs laid in the bark of the living tree; they work their way into the log and later back to the surface. The holes are cross or longitudinal sections of the channels. A single hole or channel may show, or the end of the log may be riddled.

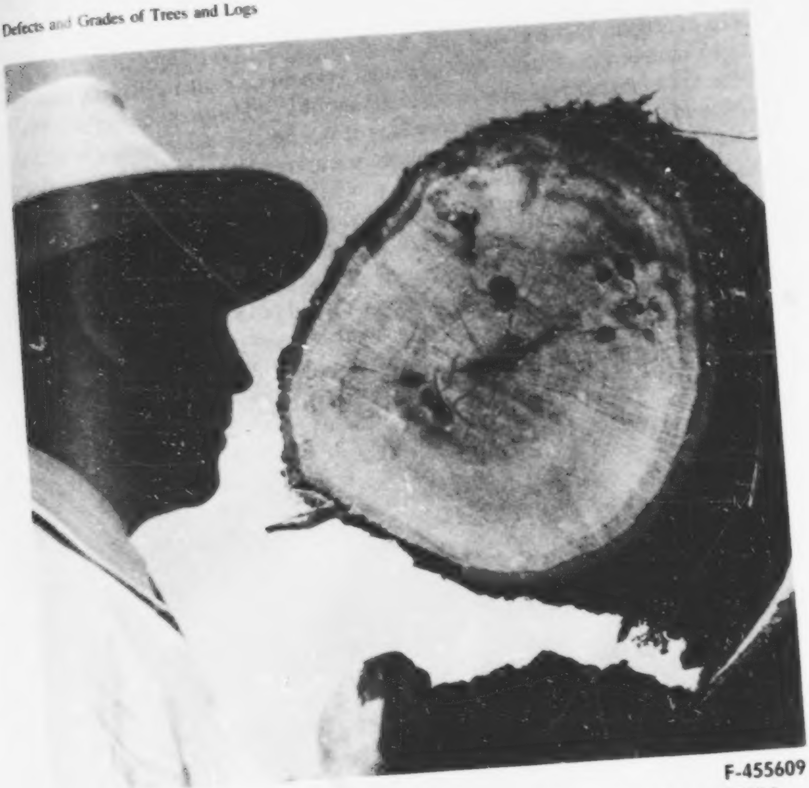

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Figure 12-32.—Concentration of grub channels. (Photo from Lockard et al. 1963.)

When grub channels are few and scattered or when a concentration is confined to the heart center, they may be disregarded in **factory logs**. Careful search, including thorough examination of the log surface, should be made to ensure that the concentration is so confined. When it is not, it is a grading defect. In extreme cases and when found in conjunction with other degraders, grub channels may cause the log to be culled. In **construction logs** concentrated grub channels in any part of the log are a log grade defect; scattered ones are not. Grub channels can be ignored in **local use logs**.

Gum **spots.—Gum spots,** found chiefly in sweetgum (particularly in the lower Coastal Plain) and black cherry, are accumulations of gum occurring as small patches, streaks, or pockets. They may be related to bird peck or other injury to the growing wood or, as in sweetgum, may be simply impregnations of the wood fibers, related to presently unidentified pathological disturbances. In sweetgum they can seldom be identified except on the end of the log.

In sweetgum **factory logs** gum spots are log grade defects when found in conspicuous concentration, for they reduce otherwise higher grades of lumber. Gum spots in cherry lumber are admitted to the "clearface" cuttings without limit and are not a defect in **factory logs** of this species. Gum spots, since they do not affect strength, are not grading defects in **construction logs** and **local use logs.**

Loose heart.—Found most frequently in chestnut, scarlet, water, and overcup oaks and in the elms and honeylocust, **loose heart** is the tangential separation of fibers completely around a growth ring within the heart center or core of the log, in an area generally not over 6 to 12 inches in diameter (fig. 12-33).

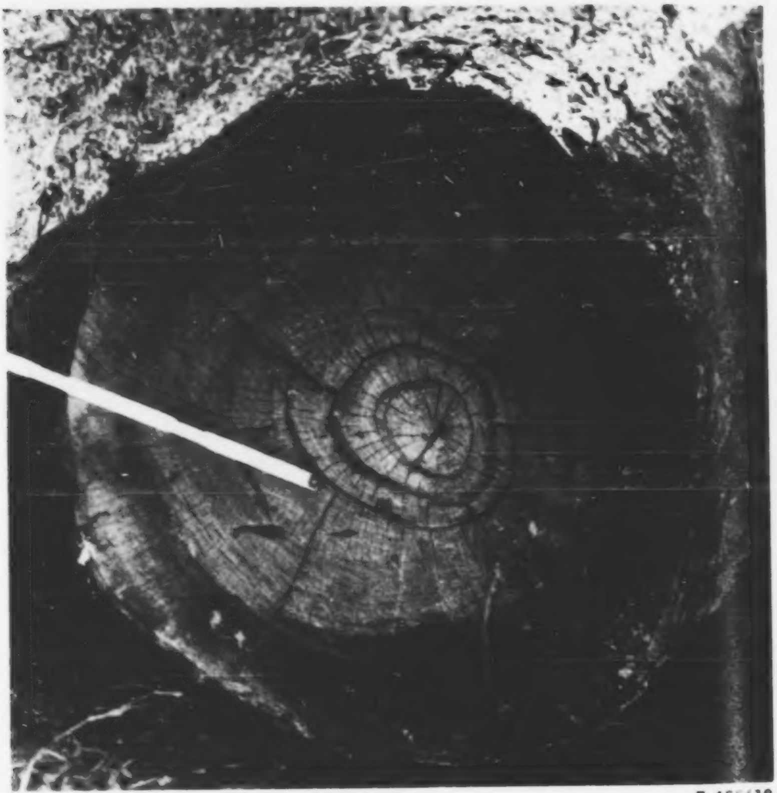
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Figure 12-33.—Loose heart. (Photo from Lockard et al. 1963.)

The area affected is well defined and must be scaled out. When loose heart is confined to the heart center, it may be disregarded in grading **factory logs.** Although the volume yield will be greatly reduced, the loose heart will in such cases have a minimal effect on average lumber grade yield. Loose heart prevents taking a tie or timber out of the center of the log and is a degrader in logs intended for this use. It may be disregarded in **local use logs** if the scale deduction is within limits. Loose heart is frequently derived from the release of crooked, suppressed saplings and follows the original stem form. Thus, it may have a disastrous effect on small, crooked, or sweepy logs, often necessitating culling the log.

Mineral streak and stain.—Mineral streak or stain, conspicuous in yellow-poplar, sweetgum, the maples, magnolias, and willows, is also found generally in the oaks—especially water oak and particularly on poor sites. It is an abnormal discoloration—black, blue, brown or olive green—usually in variegated or streaky patches confined to the heartwood (figs. 9-5 through 9-10), sometimes of bacterial origin.

In **factory logs** it is a log grade defect when conspicuously concentrated outside the heart center. A small amount there may be disregarded. In the maples, magnolias, and yellow-poplar mineral stain itself is not a lumber defect. Heavy concentrations (mineral streak), however, are often associated with fine check and shake, which are product defects. Mineral streak and mineral stain can be disregarded in **construction** and **local use logs.**

Pin worm holes.—Pin worm holes, made by ambrosia beetles, are round, and smaller than 1/16-inch in diameter (fig. 11-32).

They are most prevalent in, but not confined to, post oak, overcup and chestnut oaks, ashes, and yellow birch. Black cherry, elms, hickories, pecan, yellow-poplar, beech, sweetgum, tupelo, magnolias, cottonwood, and willow are relatively free. When pin worm holes occur, they are invariably numerous; practically all of the wood in the log will be affected.

In **factory logs** pin worm holes are log grade defects, and special grades of lumber with lowered value are used for the species in which occurrence is most common. Pin worm holes may be disregarded in **construction** and **local use logs.**

Ring shake.—Ring shake is a tangential separation of the wood fibers along parts of the annual rings (fig. 12-34). Sometimes it is confined to definite sections along the outer rim of wood, sometimes it is confined to the center, and sometimes it is found all through the log. Important ring shake is often so fine as to be invisible in green wood, and shows up only when the wood is dry.

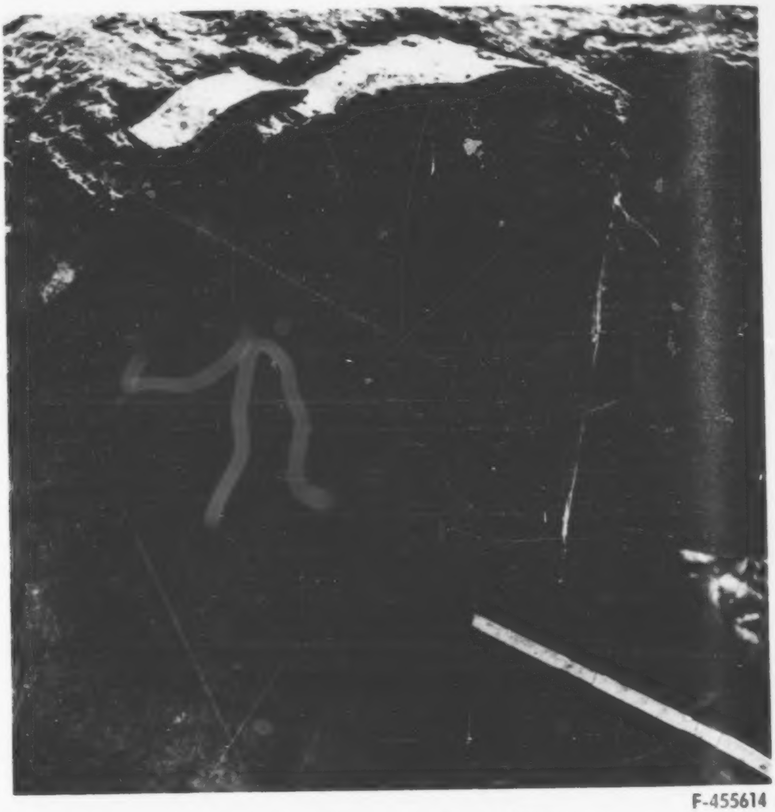

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Figure 12-34.—Ring shake. (Photo from Lockard et al. 1963.)

Although ring shake is definitely related to species, it is not found in all trees of any species. It may be found in some trees of every species, however. It seems especially prevalent in overmature, leaning, toppy, sweepy timber. Ring shake is most common in the butt log and may result from a serious butt injury. Much old-growth bitter pecan is shaky. Ring shake is also serious in overmature sycamore, tupelo, and elms, and in overcup and chestnut oak from poor sites. In Missouri, white oak has less shake than the other oak species. See Butin and Shigo (1981) for further discussion of ring shake and radial shake in oak trees.

In **factory logs** ring shake confined to the heart center or to definitely localized areas in the periphery can be scaled out. Rings shake confined to the heart center is not a grading defect, but peripheral ring shake is a degrader because it will stop cuttings. When ring shake is general throughout the log, it is a good reason to cull the log. It is a grading defect in **construction logs**. Localized shake can be disregarded in **local use logs** up to the point where the scale deduction for it exceeds that permitted in the class.

Incipient rot (dote).—**Incipient rot**, an early stage decay in which wood is discolored and weakened but does not lose its structure (fig. 12-35), can be present in any species. In woods of low density such as yellow-poplar, sweetgum, and sweetbay, decay progresses rapidly (see chapter 11 and fig. 11-18).

In both scaling and manufacturing, incipient rot is less consistently recognized than is advanced rot. Incipient rot is generally scaled out, particularly if extensive or outside the heart center. In **factory logs** such doty areas when contained in the heart center or inner half of the quality zone may be disregarded as a degrader, whether scaled out or not, whereas incipient rot in the outer half of the quality zone is a grade defect. In **construction logs** incipient rot is a grade defect, regardless of location within the log. Incipient rot may be disregarded as a log grade defect in **local use logs,** provided scale deduction for it does not exceed that allowed for the class.

Advanced rot.—Breakdown of the structure of wood characterizes **advanced rot** (fig. 12-36), which can be found in all southern hardwood species in varying amounts (figs. 11-13 through 11-17).

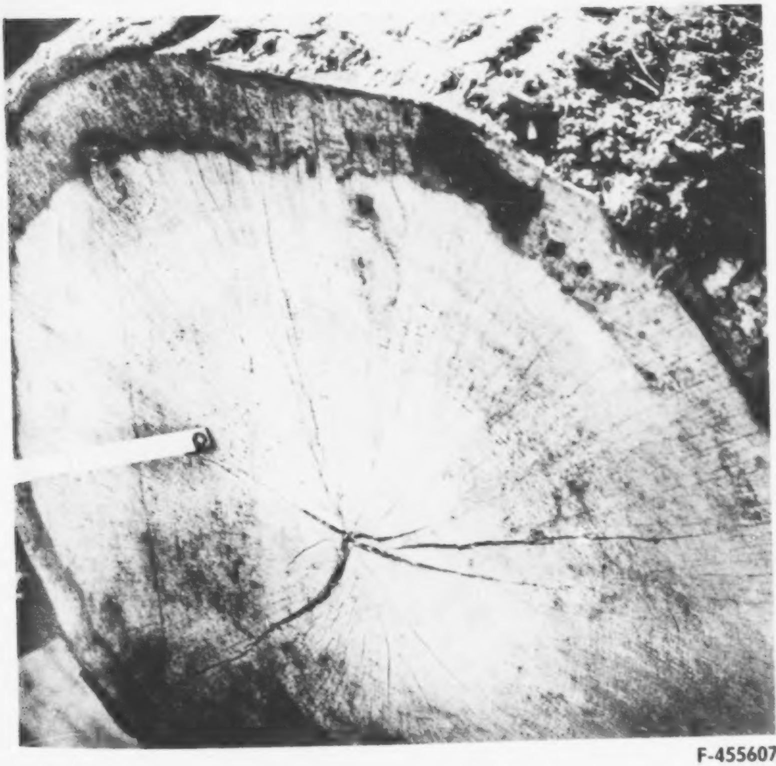

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Figure 12-35.—Incipient rot. (Photo from Lockard et al. 1963.)

Significance of advanced rot varies with use and location. In **factory logs** advanced rot confined exclusively to the heart center can be overlooked as a log grade defect. The affected section will, of course, be scaled out. Even though scale deduction is made for rot, rotten areas in the quality zone are log grade defects if they occupy over one-half the cross-sectional area in any quarter of the quality zone.

In **construction logs** advanced rot in the center is a log grade defect that, except in large diameters, probably will eliminate the log from the class. Rot in the periphery is also a degrader, unless it is so superficial that it will extend not more than 3 inches into the included tie or timber in only a few minor spots. In **local use logs** advanced rot can be disregarded providing the scale deduction does not exceed the limits for the class.

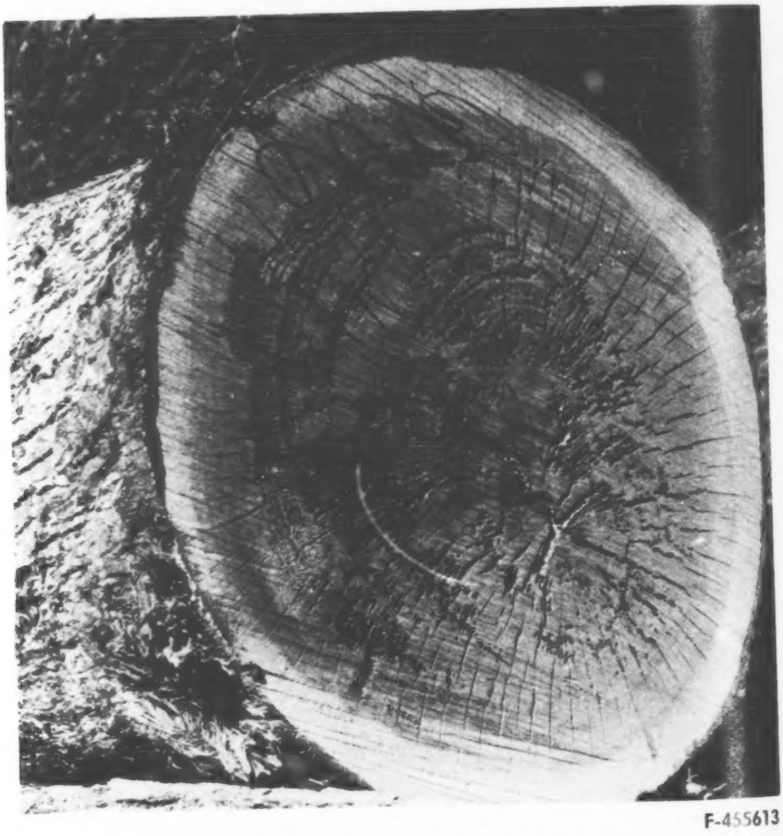

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Figure 12-36.—Advanced rot. (Photo from Lockard et al. 1963.)

Shot worm holes.—Shot worm holes, commonly found in oaks, hickories, ashes, and occasionally in sweetgum heartwood, are clean-cut round holes about 1/8-inch in diameter (fig. 12-37). They are generally concentrated in and about rotten heartwood, especially open butt wounds and hollows. Since shot worm holes are generally associated with rotten wood, they are not a degrader in **factory logs** if confined to the already degraded area. If they extend beyond the rotted section and increase the area damaged, they become log grade defects. They can be disregarded in **construction** and **local use logs** if the permitted allowance for associated rot is adequate to cover the deduction.

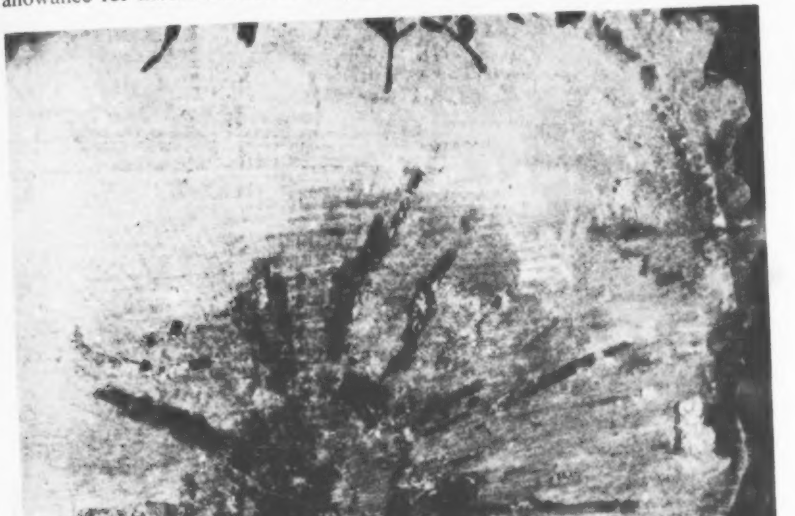

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Figure 12-37.—Shot worm holes and associated rot. (Photo from Lockard et al. 1963.)

Soak.—Most common in water and overcup oaks on poor sites, soak is a moderately discolored area, dirty mustard yellow, bleached brown, or dull gray (fig. 12-38). The wood looks dull, dead, rough, spongy, and often water soaked or weathered. Although it is considered by some as incipient decay, soak actually is not accompanied by a softening of the fibers; in fact, they are sometimes embrittled.

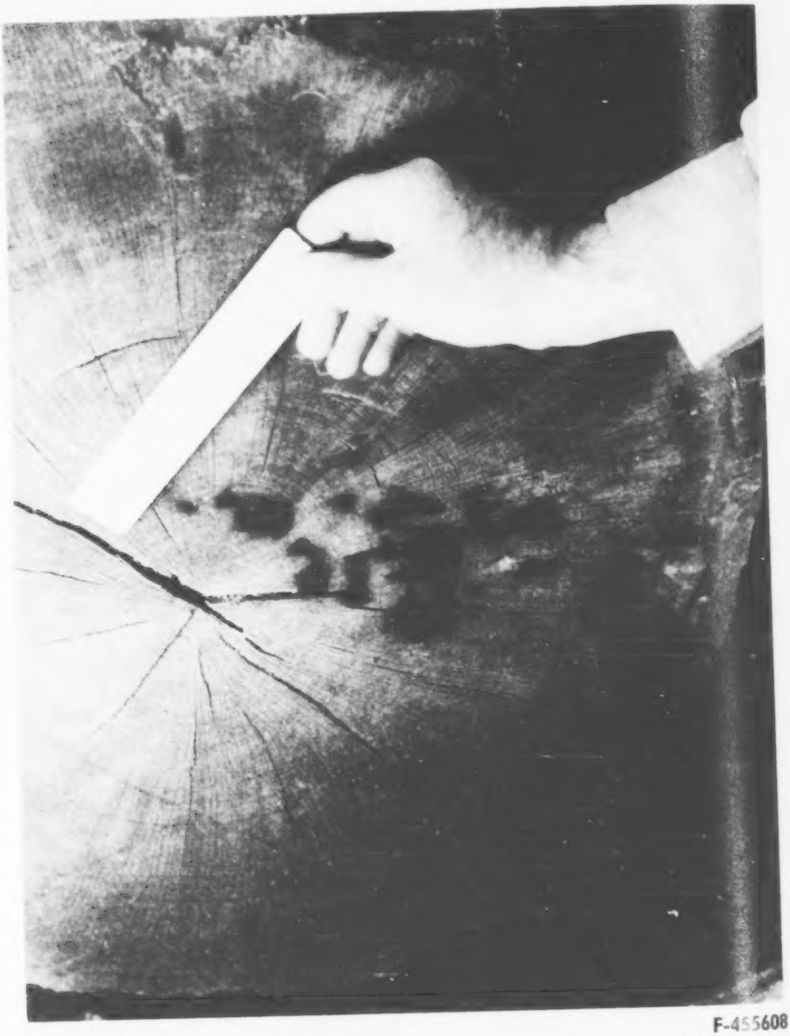
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Figure 12-38.—Soak, seen to right of ruler. (Photo from Lockard et al. 1963.)

Ordinarily no scale deduction is made for soak. In **factory lumber,** it is regarded as equal in effect to mineral stain or localized incipient rot. When heavy enough to be so considered, soak becomes a **factory log** grade defect, but can be disregarded in **construction** and **local use logs.**

Spider heart.—Most prevalent in large, mature or overmature scarlet, water, and overcup oaks, **spider heart** (fig. 12-39) also occurs in chestnut oak. It is a multiple radial separation of the wood fibers starting at the pith and extending outwardly in at least three directions. Spider heart will ruin the products in which it occurs. If it is confined to the heart center, it is not a log degrade defect in **factory logs** and in **local use logs.** When it extends beyond the heart center in **factory logs,** and when it occurs to any degree in **construction logs,** it is a degrader.

Spot or flag worm holes.—**Spot or flag worm holes** are cleancut holes about 1/32- to 1/16-inch in diameter, typically occurring in pairs (fig. 12-40). They are invariably surrounded by an oval or elongated stained or (in oaks and elms) bleached area or "flag."

In red and silver maple, post oak, and chestnut oak, spot worm will be found in almost every tree over certain extensive areas within the range of the species, but intensity will vary from tree to tree. In soft elm, beech, and white oak it occurs in small areas and in most localities is absent. White oak over most of its range is free of this defect, but damage is likely to be found on sites that are dry or lacking in lime.

In **factory logs** spot worm holes with their accompanying flags are log grade defects except in heavily damaged oaks and soft maple. In these species the lowered value of such lumber is recognized by special grades, and the holes need not be considered as log grade defects when WHND grades (Worm Holes No Defect) are used. Spot worm can be disregarded in **construction** and **local use logs.**

Wind shake.—**Wind shake** is a single radial split extending to both sides of the pith (fig. 12-41). Sometimes it is confined to the heart center, but often it will go to the perimeter of the heartwood, well into the quality zone. Damage is usually most serious in butt logs, but many times the split extends the entire length of both the butt and upper logs.

Wind shake is most serious in black oak, southern red oak, scarlet oak, and northern red oak growing on upland sites in the South, west of the Mississippi River. It is most prevalent on older trees. Wind shake is also found in some of the white oaks, particularly chestnut oak, on upland sites throughout the Appalachian region and the remainder of the South. It becomes serious near the middle of slopes and is worst on the ridgetops.

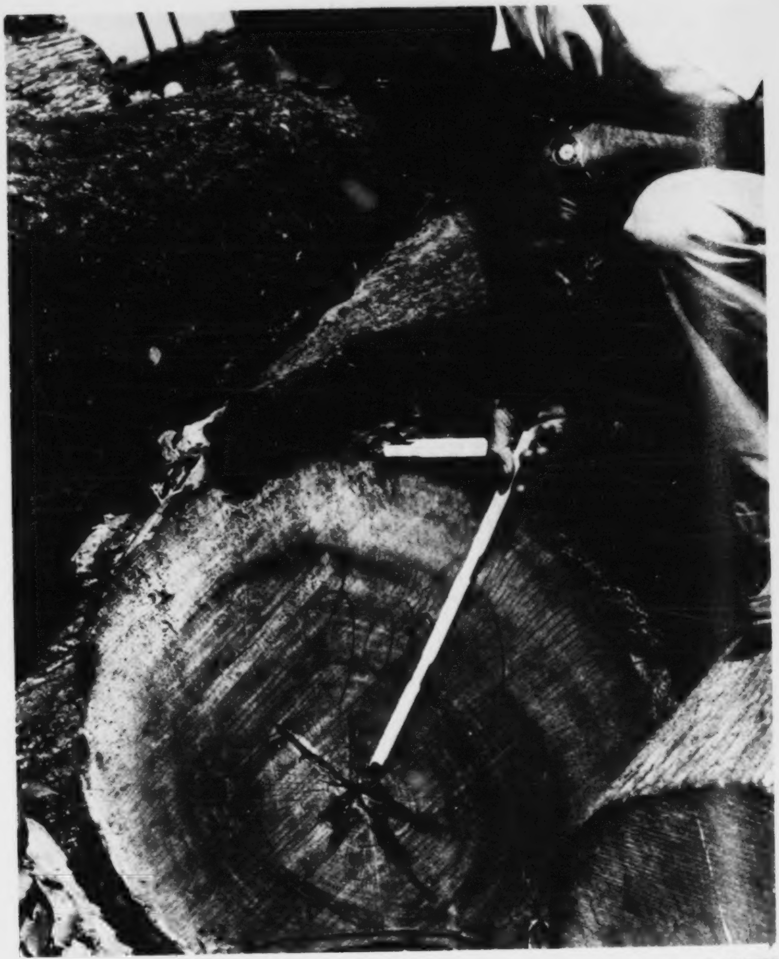

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Figure 12-39.—Spider heart. (Photo from Lockard et al. 1963.)

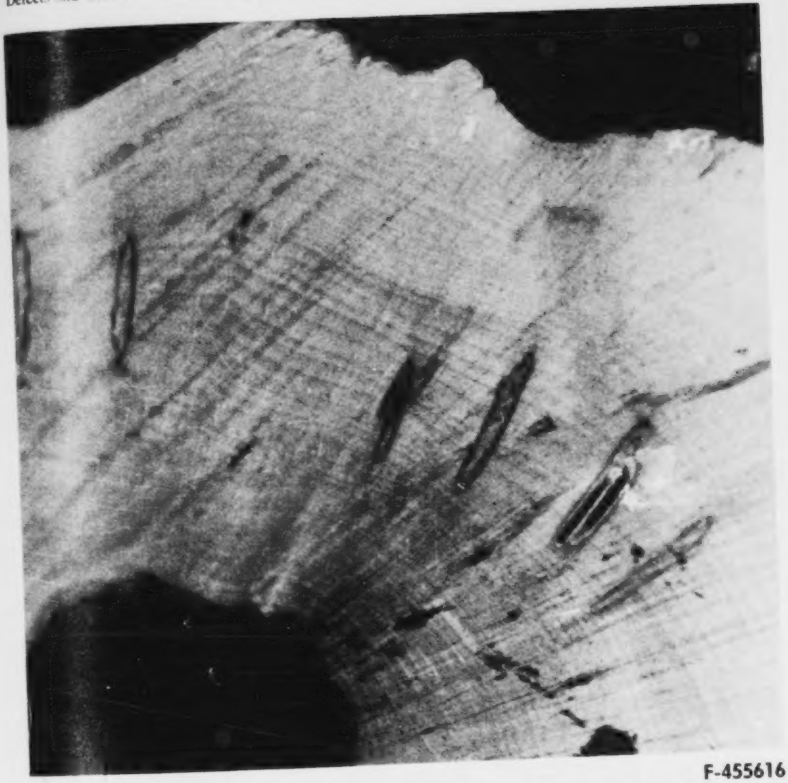

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Figure 12-40.—Spot or flag worm holes. (Photo from Lockard et al. 1963.)

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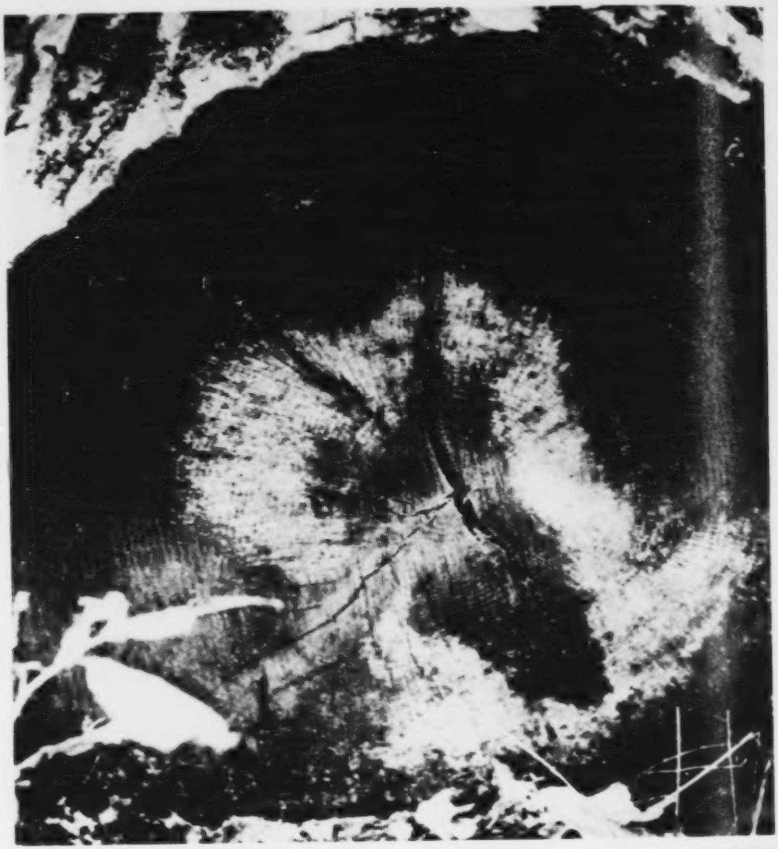

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Figure 12-41.—Wind shake. (Photo from Lockard et al. 1963.)

In **factory logs** wind shake can be scaled out, and that which is confined to the heart center is not a degrader. Where it extends to the perimeter of the heartwood in logs with a narrow sapwood band, it is a degrader because it will stop cuttings. Most wind shake is so serious that it disqualifies the log for the **construction class**. Wind shake may be disregarded in **local use logs** unless it is severe enough to cause the log to split open in handling.

GENERAL APPEARANCES THAT WARN OF LOG DEFECTS

There is a definite relationship between timber quality and site condition or history of the stand. Poor site, past fire damage, and overmaturity are often clues to the presence of such defects as insect damage, shake, or stain.

General condition and appearance of individual trees in a locality serve either as guides to hidden defects that give no other external indication of their presence (shake or mineral stain, for example) or as a warning to intensify search for important log grade defects (such as bark distortions) which cannot be seen at a glance. To appraise basic differences in appearance of standing timber requires training and familiarity with each species over a wide range of conditions. But keen observation and practice enable one to determine and recognize the characteristics of sound healthy trees and, by comparison, those of trees likely to be defective.

Obvious clues to decadence are stagheadedness, bad fire scars, and large open wounds. Less conspicuous but of the same nature are dry tops, dead limbs, healed scars, and rotten knot holes, often overgrown except for a gaping oozing center. Such features indicate decadent timber that may carry inconspicuous and unheralded defects like bark pockets, stain, and spot worm holes. When such obvious general features are present, degraders may be expected in great numbers. Evidence of these in the form of small overgrowths, often partially hidden under extended but broken bark scales, will generally be plentiful and easily located upon close examination.

In addition to the obvious features indicating decadence, less obvious general appearances are very important signs of probable log grade defects. Color, thickness, and configuration of bark, particularly if coupled with evidence of lack of vigor (dead limbs, thin top, and poor foliage), are among these (figs. 12-42, 12-43, and 12-44).

In general, abnormally dark or abnormally light bark is a bad sign. In hickories, cherrybark oak, and water oak, early stages of deterioration are evidenced by darkening of the bark, usually accompanied by thickening and roughening. In extremely advanced stages of deterioration the color trend in these species reverses, and the bark bleaches out to a dead, light gray and scales off to some extent.

In species with bark normally soft and corky, such as yellow-poplar and sweetgum, the darkening is accompanied by a “plating” and smoothing out of the bark. On the other hand, defective white oak timber in all stages of deterioration is indicated by lightening of color and thinning and scaling off of bark.

In all species bark looks dry and lifeless when vigor is lost. This condition warrants close inspection for evidence of important log grade defects. The relation of timber condition to appearance is definite and sometimes so extreme and positive that an experienced observer has no difficulty in appraising the degree of deterioration solely on this basis.

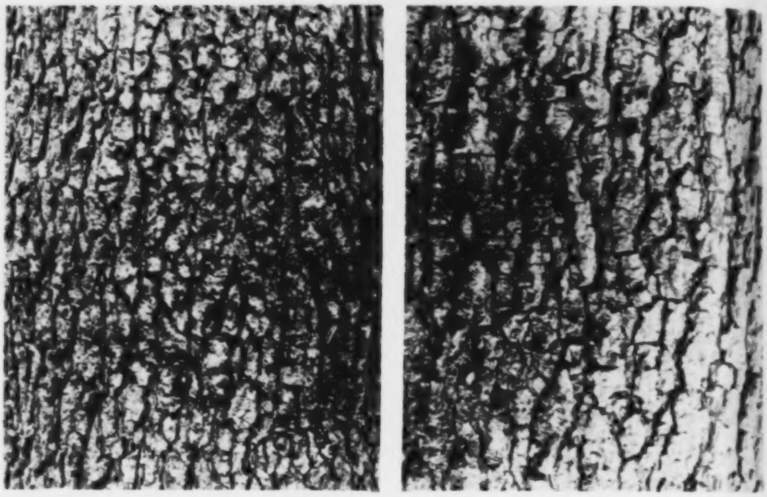

Figure 12-42.—Two 16-inch sweetgum trees, one in good condition (left) and the other poor (right) as indicated by bark characteristics. Photos taken among southern pines on an upland site in central Louisiana.

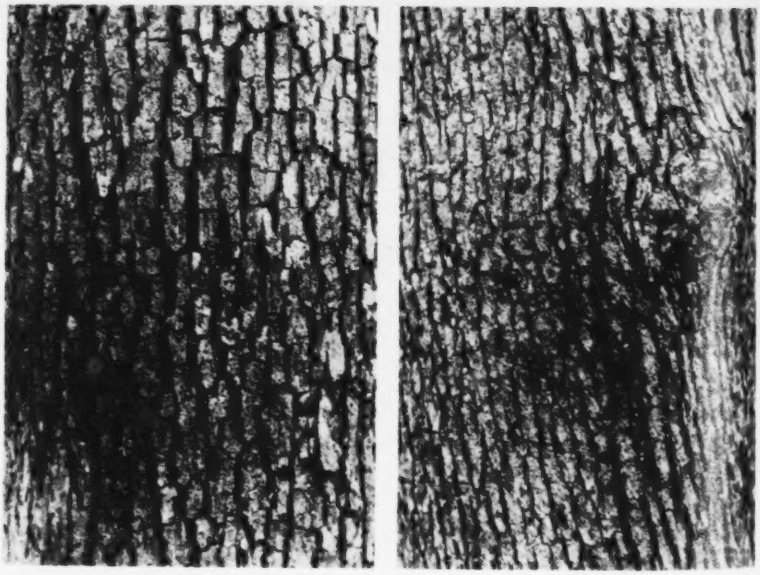

Figure 12-43.—Two 16-inch white oaks, one in good condition (left) and the other poor (right), as indicated by bark characteristics. Photos taken among southern pines on an upland site in central Louisiana.

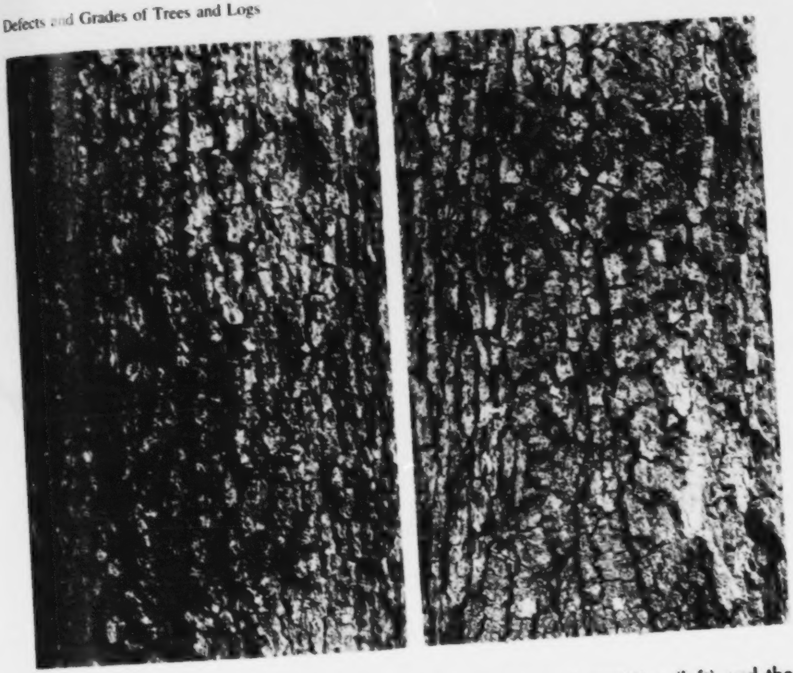

Figure 12-44.—Two 16-inch southern red oaks, one in good condition (left) and the other poor (right), as indicated by bark characteristics. Photo taken among southern pines on an upland site in central Louisiana.

Poor general appearance of bark is not an absolute indication of degraders of any specific kind, however. Yellow-poplar, sweetgum, tupelos, and basswoods (*Tilia* sp.) are rarely subject to insect attack (yellow-poplar in some localities is liable to severe attack by ambrosia beetles, the damage being referred to at times as spot worm, grease spots, blackhole, or calico poplar). In these species poor bark appearance generally indicates slow growth, approaching maturity, or if localized, rot. In fact, an area of poor bark in these species is as good a sign of rot as is a butt or stem bulge.

On the other extreme are the oaks and hickories. Here poor appearance, although a sign of lower vitality, does not reliably indicate specific location or extent of unusable material. It is, however, an almost invariable clue to hidden or obscure bark distortions. Close inspection of the bark of poor trees of these species will often reveal scattered, medium-size, dry holes that penetrate the bark scales but do not lead into the wood. It may also reveal that abnormal roughening is an effect of numerous horizontal breaks or cracks in the bark ridges or scales. In other cases bark cracks and scales containing holes will generally indicate insect-caused log grade defects. In most cases, other log grade defects will have been noted before the examination had gone that far.

In other species such as the ashes, tupelos, maples, and sycamore (*Platanus occidentalis* L.), the significance of bark appearance is quite variable. In all species, however, poor or abnormal appearance should lead to intensive search for degraders.

At least two types of local bark discolorations deserve notice. One is the so-called "tobacco juice" exudation—a small, usually damp, dark brown splotch with a drying gray border found up and down the bole. It is unmistakable evidence of fresh insect damage and can be disregarded unless the splotches are very numerous, underlain with holes extending into the wood, or accompanied by bark distortions typical of long established infestations.

The other type of local discoloration is a large patch or streak beginning at a broken top, or an open wound or knot hole in the main stem and running down the stem. When coming from a broken or hollow top of the major stem, the discoloration is usually from an overflow of rainwater. When the discoloration begins elsewhere, it is caused by water seeping from a pocket of rot. However, the mere seeping or running usually indicates that decay is not far advanced, or at least that the affected section is not an extensive hollow. Ordinarily the rot will not pass the next lower fork or body node. When the discoloration is found on the merchantable stem, however, it is a log grade defect if not cut out.

12-6 USE CLASSES FOR HARDWOOD LOGS AND TREES[4]

Specifications have been developed for four hardwood use classes: veneer, factory lumber, construction, and local use. These classes cover current utilization practices for solid wood products. The classes range in value from very high for veneer logs to low for local-use logs (figs. 12-6 and 12-45). Use-class specifications serve primarily to define a floor, or minimum quality of a log or tree, which is economically suited for a particular use.

Within a use class, subclasses or grades of logs and trees can be established. These grades are based on the yield of standard graded products recovered when the logs or trees are processed. Thus, use classes can have subclasses or grades which themselves are based on output of product grades. Without product grades there is little basis for establishing log or tree grades within a use class.

VENEER CLASS

Veneer-class logs include those suitable for either slicing or rotary peeling into veneer. The veneer may be of very high value such as that used for furniture and the faces of panels, or it may be used for lower value products such as panel backs or containers. Veneer may be graded by a system developed by the Forest Products Laboratory (Henley et al. 1963) or by a voluntary grading system (National Bureau of Standards 1972). At present, there is no standard grading system for either hardwood face veneer or container veneer.

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[4] This section is taken, with some editorial changes, from Schroeder (1981) by permission of the author and the Forest Products Research Society.

FACTORY LUMBER CLASS

The **factory lumber use class** comprises the largest proportion of all hardwood logs (fig. 12-45), i.e., those sawn into lumber graded by standard rules (National Hardwood Lumber Association 1974). Grading under these rules is based on appearance rather than strength because the lumber is usually remanufactured to remove defects and is intended for such products as furniture, cabinets, and flooring. The basic grade specifications for hardwood lumber are shown in table 12-2.

CONSTRUCTION CLASS

The **construction log use class** includes logs suitable for sawing into products where strength and utility, rather than appearance, are important. Products such as ties are graded by association rules (American Railway Engineering Association 1970). Structural lumber can also be graded using standard rules (National Hardwood Lumber Association 1978). The size of defects in the product assumes more importance in this class, especially if defects affect the strength of the piece.

LOCAL USE CLASS

The **local use log class** comprises logs of lower quality than the preceding classes; most are sawn. The products are generally not covered by grading rules and are usually marketed locally for crating, pallets, mine props, and industrial blocking.

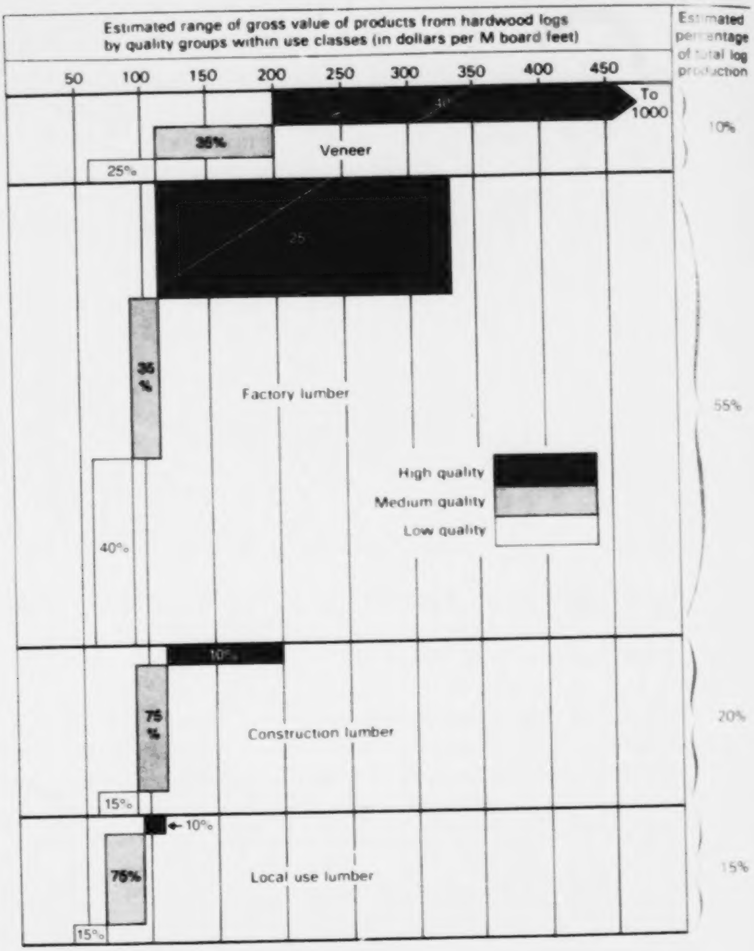

Figure 12-45.—Range in product values for the four major use classes of hardwood logs. Values for veneer are log values (dollars per thousand board feet International 1/4-inch log scale); all others are per thousand board feet of sawn air-dried lumber—1973 basis. Height of vertical bar represents proportion of log volumes. (Drawing after Rast et al. 1973.)

TABLE 12-2.—*Basic grade specifications for hardwood lumber*[1] (Rast et al. 1973)

Grade	Minimum specifications				
	Length[2]	Width	Yield of rough lumber in clear cuttings[3]	Size of cuttings	Cuttings[4]
	Feet	*Inches*	*Percent*	*Inches × feet*	*Number*
Firsts & seconds	8	6	83⅓	4" × 5' or 3" × 7'	1 to 4
Selects	6	4	Better face is seconds; reverse side of cutting is sound, or reverse side of piece is 1 Common.		
1 Common	4	3	66⅔	4" × 2' or 3" × 3'	1 to 5
2 Common	4	3	50	3" × 2'	1 to 7
Sound wormy	Full log yield of 1 Common and better, with worm holes, knots, etc. not over ¼ inch; stain admitted into cuttings.				
3A Common	4	3	33⅓	3" × 2'	No limit
3B Common	4	3	25[5]	1½" & containing not less than 36 sq. in.	No limit

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[1] The basic grade specifications for hardwood lumber were adapted from the rule book of the National Hardwood Lumber Association (Chicago, Jan. 1971-Jan. 1975), p. 17-23.

[2] Percentage of short lengths is limited by grades: for example, in Firsts only 12 percent can be 8 feet to 9 feet; in 2C, 10 percent can be 4 feet to 5 feet.

[3] A. **Clear face cutting:** A cutting having one clear face (ordinary season checks admitted) and the reverse side sound as defined in "sound cuttings." The clear face of the cutting shall be on the poor side of the board except when otherwise specified. Admissible defects: ordinary season checks, unlimited sapwood, mineral streaks and spots, burls, and stain provided it will dress out.

B. **Sound cuttings:** A cutting free from rot, pith, shake, and wane. Texture is not considered. It will admit sound knots, bird pecks, stain, streaks, or their equivalent, season checks not materially impairing the strength of the cutting, pin, shot, and spot worm holes. Other holes 1/4-inch or larger are admitted but shall be limited as follows: One 1/4-inch average diameter in each cutting of less than 12 units; two 1/4-inch or one 1/2-inch to each 12 units and on one side only of a cutting. A cutting **unit** measures 1/12th of a square foot, surface measure.

[4] Number varies with surface measure of piece; for example, in 1C with surface measure of 5 feet to 7 feet, two cuttings are allowed; in 1C with surface measure of 11 feet to 13 feet, four cuttings are allowed.

[5] On basis of sound cuttings; lumber is suitable for low-grade crating and dunnage.

12-7 HARDWOOD LOG GRADES[5]

VENEER LOG GRADES

The development of log grades based on veneer recovery has been hampered by the lack of a standard set of veneer grade specifications. Specifications for northern hardwood veneer logs have been developed by the U.S. Forest Service (table 12-3), but have not been adopted for standard use. Associations have published veneer log grade specifications (Northern Hardwood and Pine Manufacturers' Association 1968), but the systems do not relate log grade or size to veneer yield by grade.

Rast (1975) developed a preliminary veneer log grading system for yellow birch and sugar maple logs to be peeled into face veneer (table 12-4). For each of the three veneer log grades, V-1, V-2, and V-3 he predicted yields of 2 Faces Sound and Better Veneer (figs. 12-46 and 12-47). Rast noted that this veneer grade would encompass Premium, Good, and a portion of Sound decorative veneer grades described by Voluntary Product Standard PS 51-71 (see following paragraph heading *Veneer grades—decorative*); he defined the grade 2 Faces Sound and Better as follows:

Characteristic	Limitations
Sound knots	3/8-inch diameter or less
Pin knots	May contain center hole less than 1/16-inch diameter
Open splits	1/32-inch by 4 feet long or less on ends only
Tight splits or cracks	12 inches long or less
Bark pockets	Must be less than 1/16-inch wide by 1/2-inch long and hard and sound
Doze or rot	Small areas if small or sound
Rough or spiral grain, crossbreaks, or knife nicks	Must sand out
Shake	Hairline and 6 inches long or less
Stain	Any kind of water or natural end stain
Worm tracks	No limit if hard and tight
Mineral streaks or black heart	1/2-inch by 4 inches or less
Birds eye	Must be shallow

Rast's (1975) study is one of the few which relate yield of hardwood veneer to veneer log characteristics.

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[5] Text under this heading is expanded from Schroeder (1981).

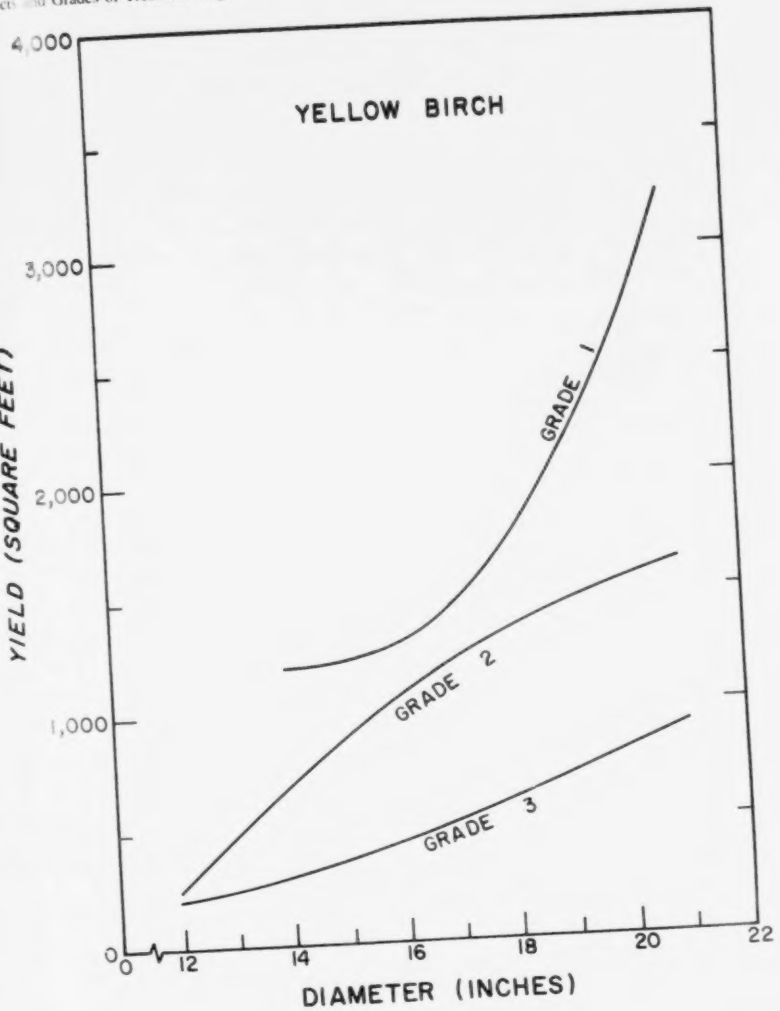

Figure 12-46.—Yield of 1/28-inch-thick grade 2 sound and better veneer from three grades of 8-foot-long, yellow-birch veneer logs. (Drawing after Rast 1975.)

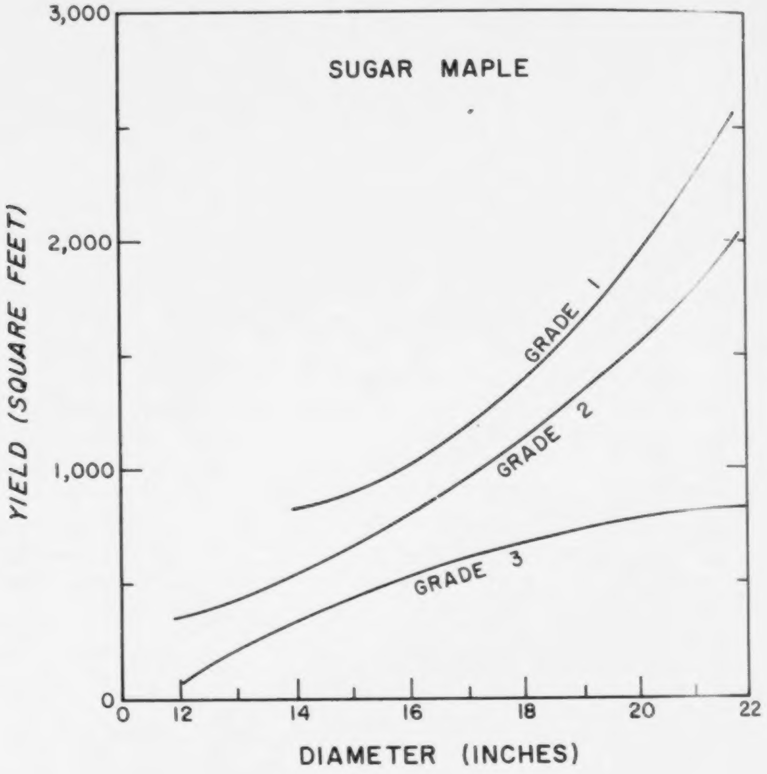

Figure 12-47.—Yield of 1/28-inch-thick grade 2 sound and better veneer from three grades of 8-foot sugar maple logs. (Drawing after Rast 1975.)

TABLE 12-3.—*Northern hardwood veneer log specification* (Rast et al. 1973[1]

Grading factors	Specifications
1. Length	8 feet and over plus 6 inches trim allowance.[2]
2. Diameter (minimum)	12 inches dib—small end[3]
3. Sweep	1/4-inch per foot of log length.
4. Crook and/or catface	One admitted in logs of all lengths and diameters if it can be contained in a 2-foot-long scaling reduction from either end, or from within the log provided that a cutting at least 52 inches long remains on each side of the scaled out portion.
5. Spiral grain (maximum)	1/2-inch per foot of log length.
6. Crotch	Crotch admitted in logs of all diameters provided it can be cut off by deducting 1 foot of length in scaling.
7. Seam	None admitted which enter the right cylinder in logs 12, 13, and 14 inches dib. Logs 15 inches dib and larger admit one seam, entering the right cylinder, provided that it diverges from a straight line between the log ends no more than 1/2-inch per foot of log length. Such a seam constitutes one standard defect.
8. Standard Defect (other than seam) Knots, worm holes, dead or rotten areas, high bumps (with height over length ratio greater than 1 to 6), heavy bark distortions and old bird pecks (four or more per square foot).[4] Treat any number as one standard defect when located not more than 10 inches from an end or so located that they can be included in a 1 foot reduction in log length when the log is scaled.	One standard defect admitted in logs 8 through 10 feet long, two in logs 12 feet, and three in logs 14 through 16 feet.
9. End Defects	
A. Black heart and/mineral stain	Admitted in hard maple logs when not in excess of one-half the scaling diameter.
B. Hole, rot, ring shake, loose or spider heart, and heart checks.	Admitted when confined to a central core around the geometric center of the log end and the last 2 feet of log length—subject to scaling reduction.[4] After scaling reduction: Logs 12, 13, and 14 inches dib can contain central core defect with long axis no longer than 3 inches; logs 15 inches dib can contain centrl core defect with long axis no longer than 4 inches; and logs 16 inches and over dib can contain central core defect with long axis no longer than 6 inches.

See footnotes on next page.

TABLE 12-3.—*Northern hardwood veneer log specification* (Rast et al. 1973)[1]
—Continued

Grading factors	Specifications
C. Knots, partial ring shake, worm holes, bird pecks, stain spots, incipient rot areas, and bark pockets.	Admitted to all logs outside the central core (9B) when confined to a one-fourth segment of one end. When occurring on both log ends, must be confined to same one-fourth segment in logs 12 through 15 inches dib, can be in different one-fourth segments in logs 16 inches dib and larger.

[1] Recommended mainly for northern hardwood species of beech, birch, maple, and cherry.

[2] 7-foot lengths of major species are accepted by most mills; 6-foot lengths of black walnut are accepted by most mills.

[3] Select Veneer Grade—Logs 14 inches and over dib—must be free of all defect except for the allowable unsound central core (9B) and sweep (3).

[4] Logs subject to 2-foot scaling reduction in length due to unsound central core (9B) permit unlimited surface defects over the 2 feet so treated (8).

TABLE 12-4.—*Proposed hardwood veneer log grades for yellow birch (Betula alleghaniensis* Britton) *and sugar maple (Acer saccharum* Marsh.*)* (after Rast 1975)

Grading factor	Proposed veneer log grades			
	V-1		V-2	V-3
Position in tree	Butts only	Uppers	Butts & Uppers	Butts & Uppers
Scaling diameter, inches	14+	16+	12+	11+
Length without trim, feet	8	—	8	8
Sweep	1/4″ per foot of log length; if more, drop 1 grade. Maximum allowed, 6″.			
Crook	2″ in 4′; if more drop 1 grade. Maximum allowed, 6″ in 4′.			
Catface	1 admitted if it can be contained in a 2′ scaling reduction from either end.			
Distortion:				
Light	No defect.			
Medium	No defect unless over 3″ in diameter.			
Spiral grain, maximum	1/2″ per foot of log length.			
Crotch	Crotch admitted in logs of all diameters provided it can be cut off by deducting 1′ of length in scaling.			
Seam	No defect if it can be contained in one face; if not, drop 1 grade.			
Defects: Knots, worm holes, dead or rotten areas, high bumps (height over length ratio greater than 1 to 6), heavy bark distortions and old bird pecks (4 or more per square feet).[1]	1 admitted.		2 admitted.	3 admitted.

TABLE 12-4.—*Proposed hardwood veneer log grades for yellow birch (Betula alleghaniensis* Britton) *and sugar maple (Acer saccharum* Marsh.) (after Rast 1975)
—Continued

Grading factor	Proposed veneer log grades		
	V-1	V-2	V-3
Treat any number as 1 defect when located not more than 10 inches from an end or so located that they can be included in a 1-foot reduction in log length when the log is scaled. Adventitious buds with no measurement and sound wounds are not defects.			
End Defects:			
Hole, loose or spider heart, and heart checks	Admitted when confined to heart center or to the last 2 feet of log length; subject to scaling reduction.		
Rot	Admitted if 4″ × 5″ (or 20 square inches or less).		
Light stain	If confined to 1/4 segment at end in quality zone,[2] no defect; otherwise drop 1 grade.		
	V-1	V-2 and V-3	
Medium or heavy stain and ring shake (if in quality zone)[2]	Confined to: Drop: 1 or 2 qtrs. 1 grade 3 or 4 qtrs. 2 grades	Drop 1 grade.	
Knots, worm holes, stain spots, soak, and bark pockets	Admitted on all logs outside the central core when confined to a 1/4 segment of one end. When occurring on both log ends, must be confined to same 1/4 segment in logs 11 through 15 inches d.i.b., can be in different 1/4 segments in logs 16 inches d.i.b. and larger.		

[1] Logs subject to 2-foot scaling reduction in length due to unsound central core permit unlimited surface defects over the 2 feet so treated.

[2] For explanation of quality zone, see figure 12-4.

Lutz (1975), in his study of the potential of pine-site hardwoods for veneer products, listed veneer-log characteristics for four classes of decorative veneer products, as follows:

- Architectural face veneer
  Logs should be at least 15 inches in diameter, 12 to 16 feet long, with clear surfaces. Ash sp. and select oak sp. are among the pine-site hardwoods used.
- Prefinished panels
  Logs should be at least 15 inches in diamater, 8 feet long, and can admit occasional pin knots, burls, gum spots, and slight mineral streaks. Sweetgum, tupelo sp., and yellow-poplar are used as well as ash sp. and oak sp.
- Furniture veneer
  Logs should be at least 15 inches in diameter, 6 feet long, with at least three-fourths of the surface clear. Species used are the same for prefinished panels.

- Finn-ply (thick plywood with one clear face, made from many thin plys)
  Logs should be about 11 inches in diameter, 4 feet long, and can admit knots to 1-1/2 inches in diameter, burls, stain, and bird peck, but should be 20 percent clear. Species could include hickory in addition to the species used for prefinished panelling.

Few pine-site hardwood logs have the diameter, length, and quality required for architectural face veneers. Some can satisfy needs for prefinished panels—particularly those given a rustic finish. Because log lengths for furniture veneer are less—6 feet, or even 4 feet—a significant supply of furniture veneer bolts can be cut from pine-site hardwoods; moreover, as technology is developed (see figs. 18-251 and 252 and sec. 28-31) to peel logs 9 to 11 inches in diameter, it is likely that the pine-site oaks can furnish significant amounts of rotary-peeled furniture veneer for 4-foot panels.

Veneer grades—decorative.—Voluntary Product Standard PS 51-71 (U.S. Department of Commerce 1972) establishes marketing classifications, quality criteria, test methods, definitions, and grade-marking and certification practices for plywood produced mainly from hardwoods. Hardwood plywood panels are constructed with an odd number of plys to produce a balanced panel; all inner plys, except the core or center ply occur in pairs having the same thickness and grain direction (fig. 22-47). Face veneers may be randomly matched or specified in a variety of patterns (fig. 22-48). Veneers are graded as Premium, Good, Sound, Utility, Backing, or Specialty.

Premium grade veneer is smooth, tight-cut, and full length. When used as a face, and when it consists of more than one piece it is edge-matched with tight joints, in patterns variable among species and with veneer cutting technique as specified in the grading rules. Characteristics permitted are defined in the grading rules but in general include small burls, occasional pin knots, color streaks or spots, and inconspicuous small patches; however, knots (other than pin knots), worm holes, rough-cut veneer, splits, shake, and decay are not permitted. Sapwood is not permitted in some classifications, e.g., sweetgum selected for red color, or plain- and rift-sliced oak.

Good grade veneer is smooth, tight-cut, and full-length. When used as a face and when consisting of more than one piece, the edge joints are tight but need not be matched for color or grain; sharp contrasts, however, in grain, figure, or natural characteristics are not permitted between adjacent pieces of veneer. Characteristics allowed are defined in the grading rules, but in general include small burls, pin knots, color streaks or spots, inconspicuous patches and usual characteristics inherent in the species; however, knots (other than pin knots), wormholes, rough-cut veneer, splits, shake, and decay are not permitted.

Sound grade veneer is free of open defects, but need not be matched for grain or color (table 22-16). **Utility grade** and **Backing grade** veneers permit some open defects as specified in table 22-16. **Specialty grade** veneer can have characteristics as agreed upon between buyer and seller; wormy, birdseye, or pecky characteristics appropriate for wall panelling generally fall in this category.

Veneer grades—structural.—It is possible to grade hardwood veneer intended primarily for structural purposes by the same rules used for southern pine veneer, as specified by the American Plywood Association (1974a) and summarized as follows:

Veneer grade	Description
A	Smooth and paintable. Neatly made repairs permissable. Also used for natural finish in less demanding applications.
B	Solid-surface veneer. Circular repair plugs and tight knots permitted.
C	Knotholes to 1-inch diameter permitted. Occasional knotholes 1/2-inch larger permitted providing total width of all knots and knotholes within a specified section does not exceed certain limits. Limited splits permitted. Minimum veneer permitted in exterior type plywood.
C-plugged	Improved C veneer with splits limited to 1/8-inch width and knotholes and borer holes to 1/4- by 1/2-inch.
D	Permits knots and knotholes to 2-1/2 inches in width and 1/2-inch larger under certain specified limits. Limited splits permitted.

Veneer-yield—structural grade basis.—Craft (1970, 1971) processed through a southern pine sheathing plywood plant a sample of factory grade 3 Appalachian mill-run oak logs cut to 8-1/2-foot lengths and averaging 11.7 inches in diameter at the small end. The sample logs scaled 3,567 board feet Doyle scale, or 4,933 board feet International 1/4-inch scale. The yield of usable veneer was 222 cubic feet, the equivalent of 2.18 square feet of 3/8-inch panels per board foot of log input, Doyle scale; or 1.50 square feet of 3/8-inch panels per board foot of log input, International 1/4-inch scale. Of the total input log volume (inside bark) of 808 cubic feet, percentage yields on a cubic basis were as follows:

Product	Percent of input volume
Usable grades C and D veneer	27
Green chippable waste, including cores	55
Dry waste	18
	100

McAlister (1981) evaluated yields and grades of 0.160-inch-thick, 8-foot-long, rotary-peeled veneer from yellow-poplar, white oak, and sweetgum 12 to 20 inches in dbh from the Georgia Piedmont, and yellow-poplar and white oak 12 to 22 inches in diameter from the mountains of North Carolina. Also, McAlister and Clark (In press) conducted a similar study of black tupelo, sweetgum, and yellow-poplar from the Coastal Plain of South Carolina. Results of these studies are shown in tables 12-5 through 12-10. McAlister (1981) summarized his **Piedmont-Mountain area** study by noting that a typical mix of 100 yellow-poplar, sweetgum, and white oak trees 12 to 20 inches in dbh and containing 3,008 cu ft of stemwood to a 4-inch top, should yield about 375 cu ft of dry C-grade and better 0.160-inch veneer; D-grade veneer from these trees should total another 233 cu ft. A typical mix of 100 trees 12 to 20 inches in diameter of the species studied in the **Coastal Plain**, with stemwood volume to a 4-inch top (dib) of 3,027 cu ft, should yield 618 cu ft of dry C-grade and better veneer, and 259 cu ft of D-grade veneer. Water oak from the Coastal Plain was eliminated from the study because fully half of the stems had severe butt rot extending from the stump upwards 4 to 6 feet.

For structural veneer, modulus of elasticity and tensile strength are of primary importance. These properties for 0.160-inch-thick, rotary-peeled sweetgum, white oak, and yellow-poplar veneers from logs harvested in three southeastern areas are shown in table 24-31.

TABLE 12-5.—*Average yield of dry, 0.160-inch-thick, rotary-peeled veneer by grade*[1] *and tree-diameter class for yellow-poplar, sweetgum, and white oak from the central Georgia Piedmont*[2] (McAlister 1981)

Tree d.b.h. (inches)	Dry veneer volume[3]				Green block volume	Green tree volume[5]	Veneer-recovery factor[6]
	AB	C	D	Fish-tail[4]			
	Cubic feet						*Percent*
			YELLOW-POPLAR				
12	0.2	1.5	0.7	0.4	11.7	24.7	20.5
14	0	6.4	2.6	.6	21.8	33.0	41.3
16	.2	10.1	3.9	1.3	34.0	45.4	41.8
18	.5	15.3	7.7	1.4	52.6	61.5	44.7
20	1.9	14.5	9.1	1.4	56.5	73.4	45.1
			SWEETGUM				
12	.2	2.2	.3	.3	7.0	19.3	38.6
14	.9	8.4	1.9	.9	24.2	34.4	46.3
16	.2	5.9	4.5	1.4	31.9	42.8	33.2
18	1.1	9.8	4.1	1.3	35.7	53.8	42.0
20	1.3	10.7	11.1	1.6	48.5	66.9	47.6
			WHITE OAK				
12	0	.72	.51	.37	8.74	17.9	14.1
14	0	2.39	.63	15.68	28.6	28.6	29.6
16	0	3.15	5.33	1.19	27.61	41.9	30.7
18	0	3.43	8.80	1.31	34.96	52.4	35.0
20	0	5.89	9.04	.84	40.54	68.9	36.8

[1] Graded by the same rules used for southern pine veneer as specified by the American Plywood Association (1974b).

[2] Each value is average for three trees; minimum top diameter of peeler blocks was about 8 inches inside bark; peeler block length was 8.75 feet; core diameter averaged 5.4 inches.

[3] Full-length veneer was 102 inches long; fishtail veneer strips were 54 inches long.

[4] "Fishtail" veneer, a size class, is used for core or crossbands; it is graded C or D.

[5] Volume to a 4-inch (dib) top.

[6] (Dry volume of full-length veneer in grades A, B, C, and D/green block volume) × 100.

TABLE 12-6.—*Average yield of dry, 0.016-inch, rotary-peeled veneer by grade*[1] *and block diameter for yellow-poplar, sweetgum, and white oak from the central Georgia Piedmont* (McAlister 1981)

Block diameter (inches)	Dry veneer volume[2]				Green block volume	Residue[4]	Veneer recovery factor[5]
	A + B	C	D	Fish-tail[3]			
	Cubic feet						*Percent*
			YELLOW-POPLAR				
9	0	0.41	0.38	0.14	4.44	3.65	18.1
10	.05	.91	.55	.18	5.13	3.63	29.4
11	.04	1.14	.94	.20	6.36	4.24	32.8
12	0	2.34	1.24	.34	7.40	3.82	48.2
13	.08	1.93	1.75	.24	8.93	5.17	41.9
14	.19	3.53	.95	.24	10.25	5.58	46.1
15	.48	4.54	1.18	.17	11.87	5.67	52.3
16	.24	4.86	1.65	.37	13.59	6.84	49.8
17	.95	6.97	1.41	.32	16.27	6.93	57.3
			SWEETGUM				
9	0	.89	.27	.20	4.63	3.47	23.8
10	.13	1.38	.65	.24	5.15	2.99	42.0
11	.17	1.66	.66	.18	6.11	3.62	39.7
12	.17	1.93	1.21	.29	7.67	4.36	42.5
13	.07	2.06	1.27	.37	9.03	5.64	37.6
14	.76	2.89	1.27	.25	10.42	5.50	48.1
15	.38	3.24	2.78	.42	11.70	5.30	54.8
16	0	1.66	4.65	.62	15.78	9.48	40.3
17	0	7.35	.22	.98	16.45	8.88	46.0
			WHITE OAK				
9	0	0	.18	.30	4.06	3.87	4.4
10	0	.49	.69	.15	5.27	4.09	21.9
11	0	.78	1.11	.30	6.81	4.91	27.0
12	0	.17	1.50	.50	7.38	5.71	22.3
13	0	1.55	2.16	.30	9.30	5.58	39.7
14	0	1.04	2.42	.39	10.05	6.59	34.4
15	0	1.56	3.00	.33	12.67	8.10	36.0
16	0	0	1.38	.07	13.48	12.10	10.2
17	0	.52	5.55	.29	15.04	8.97	40.3
18	0	4.79	3.08	.52	17.32	9.46	44.6

[1] Graded by the same rules used for southern pine veneer as specified by the American Plywood Association (1974b).

[2] Average of all blocks in diameter class obtained from trees described by footnote 2 of table 12-5.

[3] "Fishtail" veneer, a size class, is used for core or crossbands; it is graded C or D.

[4] Green block volume minus full-length veneer volume.

[5] (Dry volume of full-length veneer in grades A, B, C, and D/green block volume) × 100.

TABLE 12-7.—*Average yield of dry, 0.160-inch, rotary-peeled veneer by grade*[1] *and tree-diameter class for yellow-poplar and white oak from the southwestern North Carolina mountains*[2] (McAlister 1981)

Tree d.b.h. (inches)	Dry veneer volume[3] AB	C	D	Fish-tail[4]	Green block volume	Green tree volume[5]	Veneer recovery factor[6]
	Cubic feet						*Percent*
			YELLOW-POPLAR				
12	0	1.18	0.46	0.30	11.50	22.88	14.3
14	0	10.44	2.35	.82	31.79	44.02	40.2
16	0	15.54	10.45	1.26	51.76	57.91	50.2
18	0	16.36	12.81	2.50	64.78	77.36	45.0
20	0	18.34	18.78	1.74	76.86	96.81	48.3
22	0	20.28	31.65	2.35	98.20	110.69	52.9
			WHITE OAK				
12	0	1.82	1.69	.80	16.87	23.51	21.0
14	0	2.31	5.33	.80	28.47	36.19	26.8
16	0	3.39	8.45	.77	38.57	45.78	30.7
18	0	2.40	12.47	.62	40.83	66.58	36.4
20	0	4.90	12.24	1.72	44.30	69.27	38.7
22	0	6.97	22.48	1.76	63.05	91.43	46.7

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[1] Graded by the same rules used for southern pine veneer as specified by the American Plywood Association (1974b).

[2] Each value is average for three trees; minimum top diameter of peeler blocks was about 8 inches inside bark; peeler block length was 8.75 feet; core diameter averaged 5.4 inches.

[3] Full-length veneer was 102 inches long; fishtail veneer strips were 54 inches long.

[4] "Fishtail" veneer, a size class, is used for core or crossbands; it is graded C or D.

[5] Volume to a 4-inch top, dib.

[6] (Dry volume of full-length veneer in grades A, B, C, and D/green block volume) × 100.

TABLE 12-8.—*Average yield of dry, 0.160-inch, rotary-peeled veneer by grade* [1] *and block diameter for yellow-poplar and white oak from the southwestern North Carolina mountains* (McAlister 1981)

Block diameter (inches)	Dry veneer volume[2]				Green block volume	Residue[4]	Veneer-recovery factor[5]
	AB	C	D	Fish-tail[3]			
	Cubic feet						*Percent*
	YELLOW-POPLAR						
9	0	0.16	0.38	0.10	4.31	3.77	12.0
10	0	.52	1.18	.17	5.16	3.45	32.5
11	0	1.72	.74	.12	6.27	3.81	39.8
12	0	1.49	1.40	.28	7.39	4.50	39.5
13	0	2.44	1.96	.20	8.67	4.27	51.0
14	0	2.33	2.77	.24	9.86	4.76	51.6
15	0	2.38	3.66	.32	11.48	5.44	52.4
16	0	3.42	3.78	.42	12.89	5.69	56.0
17	0	4.70	3.11	.23	14.05	6.23	55.7
18	0	4.33	3.50	.52	16.43	8.61	47.8
19	0	5.91	4.08	.48	17.90	7.92	55.6
20	0	8.74	3.27	.20	20.81	8.80	57.7
	WHITE OAK						
9	0.57	.57	.55	.09	4.15	2.45	40.7
10	0	.25	.47	.16	5.13	4.41	14.1
11	0	.57	1.58	.24	6.31	4.16	34.1
12	0	1.06	2.04	.22	7.59	4.49	40.6
13	0	.42	1.72	.27	8.77	6.63	24.8
14	0	1.22	3.49	.22	10.62	5.91	43.7
15	0	.33	3.39	.22	11.23	7.51	33.2
16	0	1.91	4.62	.20	12.61	6.08	51.7
17	0	1.63	4.31	.56	15.01	9.07	30.0
18	0	1.44	8.14	.62	17.76	8.18	55.9
19	0	6.62	3.76	.33	20.38	10.0	50.9

[1] Graded by the same rules used for southern pine veneer as specified by the American Plywood Association (1974b).

[2] Average of all blocks in diameter class from trees described in footnote 2 of table 12-7. Full-length veneer was 102 inches long; fishtail veneer strips were 54 inches long. Blocks were 8.75 feet long; core diameter averaged 5.4 inches.

[3] "Fishtail" veneer, a size class, is used for core or crossbands; it is graded C or D.

[4] Green block volume minus full-length veneer volume

[5] (Dry volume of full-length veneer in grades A, B, C, and D/green block volume) × 100.

TABLE 12-9.—*Average yield of dry, 0.160-inch-thick, rotary-peeled veneer by grade*[1] *and tree diameter class for yellow-poplar, sweetgum, and black tupelo from the Coastal Plain (swampy) of South Carolina*[2] (McAlister and Clark In press)

Species	Tree dbh	Dry veneer volume[3] A+B	C	D	Fish-tail[4]	Green block vol.	Green tree vol.[5]	Avg. veneer recovery factor[6]
	Inches	*Cubic feet*						*Percent*
Yellow-poplar	12	0.22	2.56	0.77	0.50	11.18	23.79	32.8
	14	2.66	4.68	1.30	.56	20.98	38.64	48.1
	16	.15	8.91	6.90	.56	34.23	46.61	48.1
	18	.44	12.94	3.90	1.75	41.35	59.98	42.4
	20	1.33	15.95	6.39	1.46	42.39	67.30	58.1
Sweetgum	12	.15	1.40	2.01	.20	12.07	23.74	30.0
	14	.44	4.78	4.14	.80	27.05	38.64	35.3
	16	2.24	7.34	6.08	.91	33.82	49.59	47.9
	18	1.68	8.58	11.20	.76	42.20	64.18	52.6
	20	1.90	13.91	12.05	1.04	56.11	77.17	51.2
Black tupelo	12	.15	3.13	.39	.40	10.46	22.55	35.9
	14	.60	4.08	1.24	.50	16.36	28.33	30.9
	16	1.19	10.18	2.10	.70	32.44	44.63	42.5
	18	2.12	10.62	3.21	1.12	36.58	61.02	45.2
	20	0	12.80	3.61	2.06	37.26	66.24	45.7

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[1] Graded by the same rules used for southern pine veneer as specified by the American Plywood Association (1974b).

[2] Each value is average for three trees; minimum top diameter of peeler blocks was about 8 inches inside bark; peeler block length was 8.75 feet; core diameter averaged 5.4 inches.

[3] Full-length veneer was 102 inches long; fishtail veneer strips were 54 inches long.

[4] "Fishtail" veneer, a size class, is used for core or crossbands; it is graded C or D.

[5] Volume to a 4-inch top, dib.

[6] (Dry volume of full-length veneer in grades A, B, C, and D/green block volume) × 100.

TABLE 12-10.—*Average yield of dry, 0.160-inch-thick, rotary-peeled veneer by grade*[1,2] *and block diameter for yellow-poplar, sweetgum, and black tupelo from the coastal plains (swampy) of South Carolina* (McAlister and Clark In press)

Species	Block diam.	Dry veneer volume[3] A + B	C	D	Fish-tail[4]	Green block vol.	Green tree vol.[5]	Avg. veneer recovery factor[6]
	Inches	*Cubic feet*						*Percent*
Yellow-poplar	9	0.15	0.61	0.38	0.18	4.26	3.12	26.7
	10	0	.87	.91	.22	5.38	3.60	32.6
	11	.39	1.37	.49	.14	6.05	3.80	36.8
	12	.22	2.16	.94	.29	7.39	4.07	44.6
	13	.19	2.04	2.15	.22	8.90	4.52	49.3
	14	.06	3.65	1.63	.32	10.58	5.23	50.8
	15	0	4.96	1.03	.30	11.40	5.41	53.0
	16	1.00	6.45	1.02	.33	13.93	5.45	61.0
Sweetgum	9	0	.36	.79	.12	4.42	3.27	27.2
	10	0	.52	1.09	.11	5.09	3.48	31.6
	11	.06	.89	1.53	.18	6.36	3.88	38.5
	12	.11	1.14	1.47	.15	7.44	4.72	36.4
	13	.58	1.86	1.63	.17	8.53	4.46	47.5
	14	.85	2.20	2.56	.19	10.24	4.63	55.4
	15	.16	3.18	2.45	.24	11.59	5.81	50.0
	16	.34	2.65	3.62	.33	12.92	6.32	51.2
	17	1.19	6.00	1.58	.24	15.56	6.78	56.7
Black tupelo	9	0	1.05	.55	.21	4.25	2.65	37.5
	10	.18	1.49	.35	.17	5.44	3.43	37.5
	11	.20	1.38	.45	.26	6.37	4.34	32.4
	12	.22	1.99	1.10	.16	7.49	4.17	44.6
	13	.72	2.96	.37	.22	9.78	5.73	43.1
	14	.64	3.99	.43	.37	10.46	5.40	49.4
	15	.22	5.57	.47	.38	13.57	7.31	46.8

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[1] Graded by the same rules used for southern pine veneer as specified by the American Plywood Association (1974b).

[2] Average of all blocks in diameter class from trees described in footnote 2 of table 12-9. Full-length veneer was 102 inches long; fishtail veneer strips were 54 inches long. Blocks were 8.75 feet long; core diameter averaged 5.4 inches.

[3] "Fishtail" veneer, a size class, is used for core or crossbands; it is graded C or D.

[4] Green block volume minus full-length veneer volume.

[5] (Dry volume of full-length veneer in grades A, B, C, and D/green block volume) × 100.

FACTORY LUMBER LOG GRADES

Hardwood log grades for factory lumber were first published in 1949 by the U.S. Forest Products Laboratory and in 1952 were officially adopted by the U.S. Forest Service. The log grades are based on size (scaling diameter and length), position in the tree (butt or upper log), proportion of log surface in clear (defect-free) cuttings, and amount of scalable defect in the log (table 12-11, fig. 12-48).

Grading factory lumber logs.—The first step in grading saw logs is determination of their size (scaling diameter and length) and soundness. **Scaling diameter** is measured at the small end, inside bark.

The next step is to visually divide the log surface into four equal width full-log-length faces. Faces should be oriented so as many defects as possible are included in one face. Each face is evaluated on the proportion of the face in clear (defect-free) cuttings and cutting length. The poorest face on the log is not considered, and the grade of the log is determined by the grade of the poorest of the remaining three faces (table 12-11).

Grading the face of a log is very similar to grading hardwood lumber. In each case the grade is determined by the proportion of the piece in clear cuttings. A comparison of the clear cutting requirements for logs (table 12-11) and lumber (table 12-2) illustrates the relationship. Log grade 1 faces must have 83.3 percent of the surface in clear cuttings, the same proportion as required for a First and Seconds board. Log grade 2 faces must have 66.7 percent of the surface in clear cuttings, the same proportion as required in a No. 1 Common board. And, a grade 3 face must be 50 percent clear, the same proportion needed for a board to grade No. 2 Common.

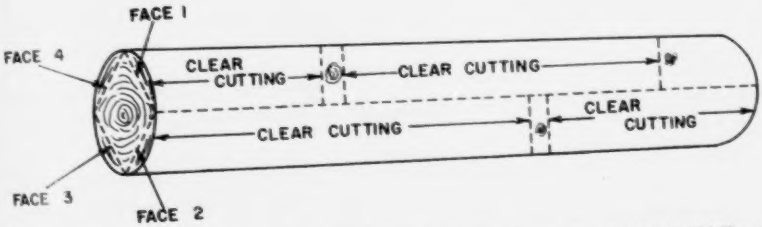

Figure 12-48.—Four log faces and definition of clear cuttings. (See table 12-11.) Knots, overgrown knots, grub holes, and other degraders are excluded from clear cuttings.

TABLE 12-11.—*Forest Service standard grades for hardwood factory lumber logs* (Vaughan et al. 1966; Hanks et al. 1980)

Grading Factors	Log Grades							
	F1			F2				F3
Position in tree	Butts only	Butts & uppers		Butts & uppers				Butts & uppers
Diameter, scaling, inches	[1]13-15	16-19	20+	[2]11	12+			8+
Length without trim, feet	10+			10+	8-9	10-11	12+	8+
Clear cuttings[3] on each of 3 best faces								
Length, min., feet	7	5	3	3	3	3	3	2
Number, maximum	2	2	2	2	2	2	3	No limit
Fraction of log length required in clear cutting	5/6	5/6	5/6	2/3	3/4	2/3	2/3	1/2
Sweep and crook allowance (maximum) in percent gross volume								
For logs with less than 1/4 of end in sound defects	15%			30%				50%
For logs with more than 1/4 of end in sound defects	10%			20%				35%
Total scaling deduction including sweep and crook	[4]40%			[5]50%				50%

End defects: See discussion under paragraph *Grading factory lumber logs*.

[1] Ash and basswood butts can be 12 inches if otherwise meeting requirements for small No. 1's.
[2] Ten-inch logs of all species can be No. 2 if otherwise meeting requirements for small No. 1's.
[3] A clear cutting is a portion of a face free of defects, extending the width of the face.
[4] Otherwise No. 1 logs with 41-60 percent deductions can be No. 2.
[5] Otherwise No. 2 logs with 51-60 percent deductions can be No. 3.

Lockard et al. (1963) and Rast et al. (1973) described relationships between end defects and log grades as summarized in the remaining text under this paragraph head.

Sound end defects, such as medium-to-heavy mineral stain in hard maple and yellow-poplar and slight dote in yellow birch on the small end of the log, shall not exceed one-half the log diameter for Grade 1 and for Grade 2 logs under 16 inches, and not exceed three-fifths the log diameter on Grade 2 logs 16 inches and larger. Excess will lower the log one grade. When the defect is not concentrated in one spot, its extent is taken as the sum of the individual occurrences.

Slight stain is not a defect.

Full-length unsound end defect outside the heart zone (taken as one-fifth the diameter from the pith), when extending more than one-half the distance between the heart zone and the bark, prevents taking clear cuttings on the face surface overlying it. When it extends less than the full log length, cuttings can be taken over a third of its estimated length from the end tapering out.

End defects, such as bird peck, worm holes, spot wormhole stain, mineral spots or streaks, and such unsound defects as grub holes and bark pockets are considered when outside the heart zone, as defined above. When these defects affect one-half the radial distance between the heart zone and the bark under three faces of the log at one end, or two faces at both ends, a log of Grade 1 or 2 shall be dropped one grade. When there is less than 3 inches either between the heart zone and the defect, or between defects, the portion will be included with the defect.

For seams, frost cracks, and fire or other scars whose depth exceeds one-fifth the diameter but not extending the full length of the log, clear cuttings can be taken over one-third of its length from the end tapering out.

Bird pecks are considered defects in cuttings of Grade 1 and Grade 2 logs when the area contains more than four bird pecks per square foot. When the depth of the bird peck on the end of the log is less than one-tenth of the log diameter, it is not considered a defect.

Lumber grade yields for sawlogs.—Using the Forest Service log grading system, tables of lumber grade yields have been developed for the following species or groups of species that can be found where southern pines grow: elm sp., black oak, chestnut oak, lowland red oak sp., upland red oak sp., lowland white oak, upland white oak, sweetgum, and yellow-poplar (tables 12-12 through 12-21). Not summarized here, but given in the source references (Vaughan et al. 1966) and Hanks et al. (1980), are grade yields for basswood (*Tilia americana* L.), yellow birch (*Betula alleghaniensis* Britton), and sugar maple (*Acer saccharum* Marsh.). Similar log grade-lumber grade tables have been developed by Schroeder and Hanks (1967) for northern red oak (table 12-22) and by Herrick (1958) for hickory sp. (table 12-23).

In summarizing information descriptive of these 11 species or species groups important where southern pines grow, only diameter classes up to 24-inch scaling diameter are here tabulated (tables 12-12 through 12-23).

Keys to abbreviations used in tables 12-12 through 12-21 are as follows:

No. of logs = actual number of logs sampled at 28 sawmills in the southern, central, and northern hardwood regions
NHLA Lumber Grade Yields (Actual) = actual lumber grade yields in percent by National Hardwood Lumber Association lumber grades
FAS = First and seconds
Sel = Select
Saps = Saps, yellow-poplar only; no restriction on amount of sapwood or heartwood
1C = No. 1 Common
2C = No. 2 Common
2A = No. 2A Common, yellow-poplar only
2B = No. 2B Common, yellow-poplar only
SW = Sound wormy
3A = No. 3A Common
3B = No. 3B Common
Tmbrs. & SSE = Ties, timbers, and sound square edges.

Lumber grade yields vary with species and log sizes within log grades. For southern hardwoods in general, the yield of No. 1 Common and Better lumber will average about 65 percent for grade 1 logs, from 40 to 64 percent for grade 2 logs, and from 13 to 39 percent for grade 3 logs.

For data on yield of furniture clear cuttings related to standard lumber grades see figures 18-126 through 18-129 and the associated entire text under the paragraph heading *Yield of cuttings*. See also figures 27-14A through 27-18B and related text in section 27-2.

For volumetric yields of lumber from various-size stems of black, northern red, white, and chestnut oaks, and red maple and yellow-poplar, see tables 18-57 through 18-62; see figures 27-9 through 27-13 and related text for additional volumetric yield data. For weight yields of red oak lumber related to lumber recovery factor, see table 22-24; see also subsections THE POUND and CONVERSION TABLES in section 27-1.

Hardwood flooring yields are graphed in figure 22-1; see also related discussion on flooring yields from graded lumber. Yield of two-ply furniture cuttings are given in figure 22-2. For quality distribution of hardwood pallet shook cut from three lumber grades by two cutting methods, see figure 22-33.

Data comparing yields when sawing hardwood logs into timbers versus sawing into lumber are given in figures 22-50 through 22-52 and associated discussion.

Yields of 2 × 4 studs cut from small yellow-poplar logs, by volume and grade, are shown in tables 22-27 and 22-28.

Other yield data are given in section 27-2 and in the materials balance diagrams of sections 28-4, 28-8, 28-11, 28-12, 28-13, 28-15, 28-17, 28-18, 28-22, and 28-26.

TABLE 12-12.—*Elm sp. lumber grades related to Forest Service saw log grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]

No. of logs	Scaling diameter	NHLA lumber grade yields (actual) FAS	Sel	1C	2C	3A	3B	Tmbrs. and SSE
	Inches	*Percent*						
		LOG GRADE 1						
22	13	12.6	6.8	36.7	23.1	7.5	13.3	—
32	14	27.0	11.5	28.7	12.8	2.9	17.1	—
25	15	26.2	11.4	30.5	15.1	2.5	14.3	—
44	16	20.9	10.4	28.9	17.9	6.2	15.7	—
41	17	29.1	10.3	27.9	15.3	1.6	15.8	—
29	18	30.9	8.8	24.1	14.5	2.7	18.5	.5
25	19	30.0	5.3	30.4	14.9	1.2	18.2	—
22	20	25.8	12.8	29.2	16.6	1.6	14.0	—
12	21	37.7	6.9	25.6	19.7	—	10.1	—
15	22	34.9	6.5	26.1	17.0	—	15.5	—
5	23	49.7	5.1	22.4	6.7	—	16.1	—
3	24	25.9	14.1	35.0	11.7	—	13.3	—
		LOG GRADE 2						
24	10	3.4	1.9	24.5	32.0	1.3	36.9	—
59	11	4.2	3.8	27.9	28.6	7.0	28.5	—
63	12	8.0	3.5	29.4	26.3	8.6	24.2	—
66	13	6.6	4.2	34.9	26.1	6.8	21.4	—
64	14	3.9	5.3	32.7	30.1	6.0	19.8	2.2
47	15	12.5	5.7	28.5	26.9	5.4	20.1	.9
23	16	5.3	6.5	35.3	31.2	6.9	14.8	—
23	17	10.0	3.2	33.1	29.6	4.9	19.2	—
15	18	13.6	9.2	41.4	21.1	3.5	11.2	—
8	19	10.1	2.2	49.3	23.2	5.1	10.1	—
5	20	13.1	4.5	39.8	25.5	7.4	9.7	—
4	21	3.2	—	40.7	25.8	—	30.3	—
1	22	10.7	17.4	30.1	29.1	—	12.7	—
1	23	9.4	—	29.2	37.0	22.8	1.6	—
		LOG GRADE 3						
5	8	—	—	8.9	31.5	3.2	56.4	—
28	9	—	.5	14.2	27.8	8.0	49.5	—
42	10	1.9	1.1	16.8	33.2	10.8	36.2	—
10	11	—	—	3.8	51.9	1.6	42.7	—
13	12	1.6	2.0	21.2	41.2	13.0	21.0	—
10	13	2.7	—	16.1	41.3	5.0	34.9	—
3	14	—	—	27.8	48.9	—	23.3	—
6	15	—	6.5	15.0	40.9	4.6	33.0	—
8	16	10.3	.4	21.5	42.5	7.8	17.5	—
3	17	—	—	15.8	51.3	.9	32.0	—
2	18	5.1	—	15.7	45.6	—	33.6	—
2	19	—	—	23.8	38.2	4.9	33.1	—

[1] Lumber graded green. See text for meaning of abbreviations.

TABLE 12-13.—*Black oak lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]

No. of logs	Scaling diameter	NHLA lumber grade yields (actual)							
		FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches				*Percent*				
				LOG GRADE 1					
15	13	25.6	10.1	25.3	15.9	—	8.2	12.5	2.4
20	14	22.6	9.5	26.6	13.9	—	5.7	16.1	5.6
20	15	25.4	11.6	29.2	13.8	—	5.5	14.5	—
30	16	23.4	10.4	27.1	15.2	—	6.8	17.1	—
29	17	23.0	11.5	27.4	15.1	—	5.3	17.0	.7
15	18	24.8	7.9	31.5	14.3	—	6.8	14.7	—
22	19	30.9	10.4	27.8	10.6	—	3.1	11.0	6.2
19	20	30.3	6.2	38.6	9.2	—	5.0	10.7	—
9	21	38.8	6.5	32.0	10.1	—	3.9	8.7	—
7	22	37.9	5.5	42.4	4.1	—	1.1	9.0	—
2	23	29.1	7.7	37.5	10.2	—	3.2	12.3	—
2	24	20.7	5.7	59.0	5.5	—	2.0	7.1	—
				LOG GRADE 2					
1	10	—	—	18.9	43.4	—	—	37.7	—
17	11	3.5	7.5	16.4	23.2	—	11.6	37.8	—
33	12	4.5	2.4	17.9	23.5	—	9.5	42.2	—
23	13	3.2	2.4	22.5	20.1	—	12.6	37.3	1.9
39	14	3.9	2.8	23.0	18.0	—	8.2	44.1	—
46	15	5.6	3.7	22.4	21.6	.2	8.2	38.3	—
31	16	2.3	4.1	22.7	17.8	—	8.3	44.8	—
22	17	4.5	1.4	24.8	21.6	—	6.4	39.5	1.8
13	18	5.2	7.3	36.6	17.4	—	10.1	23.4	—
12	19	7.4	3.4	33.4	15.5	2.4	8.7	26.5	2.7
6	20	13.8	1.4	23.1	22.7	—	9.7	29.3	—
2	21	—	1.8	28.0	28.2	—	13.4	28.6	—
				LOG GRADE 3					
5	8	—	—	—	13.5	—	5.4	81.1	—
8	9	—	—	8.7	16.7	—	10.7	63.9	—
14	10	—	—	12.8	19.1	—	15.6	52.5	—
8	11	—	2.2	7.7	15.7	—	10.2	64.2	—
13	12	.8	.7	14.5	23.5	—	10.8	49.7	—
10	13	—	1.1	11.6	24.6	—	13.9	48.8	—
11	14	1.0	—	22.4	23.6	—	13.0	40.0	—
7	15	.9	—	15.1	19.2	4.0	11.0	49.8	—
6	16	3.8	1.3	25.3	28.4	—	14.8	26.4	—
—	17	—	—	—	—	—	—	—	—
2	18	—	13.0	37.1	27.2	—	4.0	5.7	13.0
2	19	—	—	2.6	9.2	—	3.9	84.3	—
3	20	4.4	1.6	21.5	21.4	—	13.1	32.8	5.2

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[1] Lumber graded green. See text for meaning of abbreviations.

TABLE 12-14.—*Chestnut oak lumber grades—worm holes considered a defect—related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]

No. of logs	Scaling diameter	NHLA lumber grade yields (actual)							
		FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches				*Percent*				
		LOG GRADE 1							
5	13	23.2	21.0	22.9	11.5	3.0	3.6	8.5	6.3
1	14	—	—	58.9	41.1	—	—	—	—
1	15	7.3	10.9	21.8	25.5	—	34.5	—	—
2	16	15.7	8.0	31.3	13.6	5.5	3.4	22.5	—
2	17	12.8	13.9	32.6	—	11.9	3.2	—	25.6
1	18	—	24.8	31.0	11.6	24.8	7.8	—	—
2	19	25.2	7.6	12.4	28.5	6.8	14.7	4.8	—
3	20	14.5	8.1	40.7	7.0	13.9	8.5	7.3	—
1	21	27.4	17.7	10.4	29.3	3.6	11.6	—	—
2	22	10.3	1.6	54.0	13.1	9.1	3.4	8.5	—
		LOG GRADE 2							
5	10	—	1.2	34.8	42.2	3.3	12.7	5.8	—
12	11	—	—	18.2	22.8	8.6	18.2	16.4	15.8
10	12	1.4	1.9	27.8	20.1	19.9	10.0	18.9	—
7	13	4.7	1.9	14.7	15.5	10.0	17.5	35.7	—
9	14	1.1	—	10.0	17.4	12.4	23.1	26.3	9.7
10	15	2.3	2.7	11.9	25.9	19.6	12.5	21.5	3.6
5	16	2.8	.9	24.3	18.5	28.1	8.0	17.4	—
2	17	—	—	5.4	12.6	22.4	34.3	25.3	—
5	18	3.7	1.6	27.5	21.2	13.4	11.9	20.7	—
6	19	5.2	2.7	31.0	18.0	13.7	13.2	16.2	—
4	20	—	—	8.6	24.4	41.2	6.4	19.4	—
4	21	2.1	1.8	19.4	11.0	32.9	3.7	29.1	—
—	22	—	—	—	—	—	—	—	—
1	23	12.4	15.0	30.3	5.9	9.4	2.9	7.5	16.6
4	24	—	—	16.0	10.9	33.3	7.4	9.5	22.9

Table continued on next page.

TABLE 12-14.—*Chestnut oak lumber grades—worm holes considered a defect—related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]—Continued

		NHLA lumber grade yields (actual)							
No. of logs	Scaling diameter	FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches	*Percent*							
		LOG GRADE 3							
4	8	—	—	3.5	13.2	—	14.0	69.3	—
14	9	—	—	11.0	18.8	5.1	17.7	33.8	13.6
13	10	—	—	3.0	19.3	12.4	23.3	33.0	9.0
14	11	—	.7	6.7	11.5	27.5	16.1	27.5	10.0
9	12	—	.8	7.8	12.3	35.4	6.8	24.0	12.9
12	13	—	—	2.7	8.3	32.3	31.7	20.4	4.6
10	14	1.1	3.8	7.7	10.8	34.7	16.0	23.2	2.7
6	15	—	—	4.2	3.8	52.5	15.1	15.0	9.4
5	16	—	—	9.1	13.8	33.7	16.7	20.7	6.0
3	17	—	—	6.8	19.4	41.4	21.3	11.1	—
6	18	—	—	5.4	7.7	38.1	13.3	23.4	12.1
4	19	—	—	2.5	—	46.1	15.4	36.0	—
5	20	—	—	3.7	18.3	24.3	29.0	24.7	—
2	21	—	—	5.9	13.4	53.1	12.8	14.8	—
—	22	—	—	—	—	—	—	—	—
3	23	—	—	4.1	5.7	54.5	11.0	24.7	—
2	24	—	—	3.9	7.9	42.5	11.9	22.7	11.1

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[1] Lumber graded green. See text for meaning of abbreviations.

TABLE 12-15.—*Chestnut oak lumber grades—worm holes considered no defect—related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]

		NHLA lumber grade yields (actual)							
No. of logs	Scaling diameter	FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches	*Percent*							
		LOG GRADE 1							
5	13	23.2	21.0	24.3	11.5	1.6	3.6	8.5	6.3
1	14	—	—	58.9	41.1	—	—	—	—
1	15	7.3	10.9	30.8	25.5	—	25.5	—	—
2	16	22.4	8.0	30.1	13.6	—	3.4	22.5	—
2	17	45.6	14.0	11.6	1.5	—	1.7	—	25.6
1	18	20.2	10.9	49.5	17.8	—	1.6	—	—
2	19	28.5	7.6	27.7	16.7	—	14.7	4.8	—
3	20	21.6	8.1	47.4	9.8	—	5.8	7.3	—
1	21	27.4	17.7	14.1	32.9	—	7.9	—	—
2	22	21.2	1.6	52.2	13.1	—	3.4	8.5	—

TABLE 12-15.—*Chestnut oak lumber grades—worm holes considered no defect—related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]—Continued

No. of logs	Scaling diameter	NHLA lumber grade yields (actual) FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches	...*Percent*...							
		LOG GRADE 2							
5	10	—	1.2	41.0	39.3	—	12.7	5.8	—
12	11	3.2	—	16.8	23.7	6.7	17.3	16.4	15.9
10	12	8.5	1.9	36.7	22.3	3.9	7.8	18.9	—
7	13	6.7	3.0	21.6	21.8	—	11.2	35.7	—
9	14	7.0	.6	15.2	19.4	4.5	18.1	25.5	9.7
10	15	8.0	3.9	27.1	19.7	5.9	10.3	21.5	3.6
5	16	27.4	1.8	27.8	21.1	—	4.5	17.4	—
2	17	—	2.5	25.3	31.0	—	15.9	25.3	—
5	18	23.0	4.2	19.1	23.6	—	9.5	20.6	—
6	19	7.5	2.7	42.4	21.2	—	10.1	16.1	—
4	20	38.5	3.3	21.2	13.8	—	3.8	19.4	—
4	21	22.1	3.5	34.6	6.0	.8	3.7	29.3	—
—	22	—	—	—	—	—	—	—	—
1	23	17.3	15.0	34.9	5.9	—	2.9	7.4	16.6
4	24	23.4	1.5	27.1	10.1	1.1	4.5	9.4	22.9
		LOG GRADE 3							
4	8	—	—	3.5	13.2	—	14.0	69.3	—
14	9	—	.9	15.3	20.8	—	15.6	33.8	13.6
13	10	—	1.9	13.1	25.0	2.7	16.8	31.5	9.0
14	11	4.2	2.3	29.5	13.5	—	13.0	27.5	10.0
9	12	3.0	1.4	35.3	17.3	4.8	1.4	24.0	12.8
12	13	6.0	—	25.5	26.2	4.0	13.3	20.4	4.6
10	14	16.2	5.1	25.9	8.4	3.2	15.3	23.2	2.7
6	15	20.4	—	36.6	13.3	—	5.4	15.0	9.3
5	16	—	—	40.0	27.2	1.9	4.1	20.8	6.0
3	17	19.1	—	29.1	32.7	—	8.0	11.1	—
6	18	20.8	2.1	24.1	14.1	—	3.2	23.5	12.2
4	19	6.7	—	40.0	6.5	—	10.8	36.0	—
5	20	6.8	—	21.8	25.6	—	21.2	24.6	—
2	21	36.9	4.5	17.6	21.2	—	5.0	14.8	—
—	22	—	—	—	—	—	—	—	—
3	23	7.1	1.0	51.5	15.7	—	—	24.7	—
2	24	2.8	—	46.2	15.4	—	1.8	22.7	11.1

[1] Lumber graded green. See text for meaning of abbreviations.

TABLE 12-16.—*Red oak sp. (lowland) lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]

No. of logs	Scaling diameter	NHLA lumber grade yields (actual) FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches	..............................*Percent*..............................							
		LOG GRADE 1							
16................	13	15.0	7.4	31.9	21.3	—	7.8	11.8	4.8
25................	14	26.6	9.3	26.7	16.4	—	7.5	7.4	6.1
32................	15	23.2	11.3	29.5	13.7	.2	6.2	7.1	8.8
60................	16	18.9	9.9	31.2	15.2	—	9.9	9.3	5.6
40................	17	29.4	7.5	28.2	14.9	—	7.9	4.6	7.5
34................	18	25.1	9.7	32.1	12.3	—	4.2	5.2	11.4
29................	19	30.7	6.4	34.4	13.2	—	6.8	4.3	4.2
27................	20	33.8	8.5	26.5	10.6	.9	5.0	8.4	6.3
16................	21	40.3	7.6	26.5	8.0	—	2.5	5.1	10.0
13................	22	30.1	6.3	34.9	10.7	—	5.3	10.3	2.4
		LOG GRADE 2							
2................	10	—	7.9	33.1	15.7	—	27.6	15.7	—
35................	11	6.2	4.5	27.8	23.4	—	12.4	14.8	10.9
55................	12	5.3	3.7	30.2	22.2	—	12.9	18.1	7.6
68................	13	5.0	4.2	26.8	24.3	—	14.8	17.2	7.7
57................	14	7.1	5.0	28.4	23.4	.5	14.5	18.3	2.8
72................	15	5.7	4.1	29.1	23.4	—	14.9	14.9	7.9
40................	16	4.8	6.0	39.4	20.8	.4	10.8	12.0	5.8
33................	17	8.3	6.0	33.6	17.7	.2	9.4	17.7	7.1
30................	18	8.0	3.8	40.9	16.5	—	9.0	12.3	9.5
22................	19	10.1	4.8	34.6	22.6	—	13.0	12.1	2.8
5................	20	12.2	2.7	27.8	19.0	—	14.0	21.0	3.3
4................	21	3.8	8.2	35.1	20.0	2.5	14.5	8.8	7.1
4................	22	11.8	4.0	35.5	18.4	—	10.3	7.8	12.2
1................	23	3.4	4.1	38.6	30.0	—	4.1	4.1	15.7
6................	24	8.9	3.2	50.2	16.1	—	8.4	6.2	7.0
		LOG GRADE 3							
7................	8	—	—	19.7	8.4	—	11.7	36.9	23.3
10................	9	1.6	1.6	14.1	20.4	—	8.3	32.0	22.0
20................	10	1.2	1.2	21.4	20.7	—	16.0	25.9	13.6
15................	11	—	1.5	12.6	32.9	—	24.5	25.9	2.6
15................	12	—	.4	19.3	32.1	—	20.4	21.5	6.3
28................	13	.7	.6	9.8	22.0	—	24.2	35.6	7.1
24................	14	1.2	.7	13.5	23.7	.2	21.3	33.4	6.0
15................	15	.4	.7	24.7	30.3	—	19.2	19.4	5.3
5................	16	—	—	23.5	24.3	—	23.6	28.6	—
12................	17	.8	2.9	32.4	31.7	—	9.9	16.7	5.6
6................	18	3.1	4.9	22.2	21.8	—	19.3	23.0	5.7
3................	19	—	.8	46.0	22.1	—	12.8	18.3	—
6................	20	.8	.7	27.2	30.9	—	17.4	23.0	—
1................	21	—	—	34.3	26.6	—	21.2	17.9	—
2................	22	—	—	34.0	41.9	—	15.9	8.2	—

[1] Lumber graded when green. See text for meaning of abbreviations.

TABLE 12-17.—*Red oak sp. (upland) lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]

No. of logs	Scaling diameter	NHLA lumber grade yields (actual) FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches	*Percent*							
		LOG GRADE 1							
32.	13	19.6	12.9	26.0	13.8	—	8.9	17.4	1.4
16.	14	35.1	13.2	22.0	12.7	—	7.7	9.3	—
26.	15	29.6	13.9	25.7	9.8	—	6.9	12.8	1.3
43.	16	37.4	12.6	24.7	11.1	—	6.2	6.5	1.5
35.	17	37.1	11.9	22.8	11.0	—	6.4	10.2	.6
27.	18	37.3	9.2	26.1	10.4	—	4.4	10.6	2.0
30.	19	32.3	6.5	34.2	10.2	—	4.1	9.8	2.9
22.	20	38.1	9.6	25.5	10.9	—	3.4	11.5	1.0
21.	21	40.4	6.3	26.6	10.2	—	3.2	11.7	1.6
19.	22	35.8	6.2	28.3	11.7	—	5.2	11.8	1.0
13.	23	42.8	5.6	27.5	10.6	—	4.2	8.5	.8
15.	24	37.9	5.2	30.2	12.0	—	3.3	10.4	1.0
		LOG GRADE 2							
15.	10	8.9	15.8	30.1	13.8	1.3	9.7	20.4	—
65.	11	3.6	4.7	28.8	26.2	—	14.6	20.9	1.2
80.	12	4.3	6.4	29.0	19.8	—	13.5	22.9	4.1
54.	13	6.7	4.6	28.1	19.7	1.5	11.1	28.3	—
65.	14	8.6	6.0	34.6	22.1	.3	9.7	15.9	2.8
67.	15	10.4	7.3	31.8	19.1	—	7.7	23.7	—
39.	16	7.8	4.5	27.7	21.2	—	9.9	27.6	1.3
35.	17	10.1	5.5	30.1	14.3	—	8.9	30.9	.2
22.	18	10.9	1.8	30.9	22.2	.3	7.0	26.9	—
25.	19	12.4	4.1	38.7	17.4	—	6.7	20.4	.3
11.	20	7.1	3.3	35.7	21.7	—	6.2	19.3	6.7
5.	21	16.9	4.1	27.1	8.6	—	4.7	38.6	—
6.	22	15.2	.7	36.8	18.5	—	3.4	25.4	—
4.	23	7.3	.7	28.6	22.7	—	6.2	34.5	—
4.	24	10.1	5.1	53.4	14.8	—	1.6	12.4	2.6

Table continued on next page.

TABLE 12-17.—*Red oak sp. (upland) lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]—Continued

No. of logs	Scaling diameter	NHLA lumber grade yields (actual) FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches	*Percent*							
		LOG GRADE 3							
11	8	2.4	2.1	15.2	24.7	1.5	7.4	46.7	—
23	9	.6	.9	19.5	27.3	.9	14.6	36.2	—
45	10	—	.4	17.9	25.1	.3	15.8	40.5	—
13	11	—	.7	11.3	17.6	—	13.6	56.8	—
26	12	—	1.0	18.3	25.9	—	17.7	37.1	—
21	13	—	.6	8.4	27.0	—	16.7	45.6	1.7
22	14	.5	—	11.5	22.3	—	15.2	50.5	—
14	15	.3	.4	9.2	19.2	—	9.8	54.5	6.6
17	16	—	.4	12.7	24.4	—	11.8	50.7	—
7	17	2.5	2.4	21.3	26.1	—	8.9	27.5	11.3
5	18	5.4	—	17.7	21.1	—	10.2	45.6	—
7	19	.6	—	25.4	26.3	—	5.8	41.9	—
2	20	—	—	1.9	19.3	—	3.0	75.8	—
6	21	—	1.0	20.2	34.7	—	10.4	33.7	—
1	22	—	—	7.7	18.9	—	15.8	57.6	—
2	23	—	—	50.5	25.3	—	13.2	11.0	—
1	24	—	—	26.1	30.9	—	12.5	30.5	—

[1] Lumber graded when green. See text for meaning of abbreviations.

TABLE 12-18.—*White oak (lowland) lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]

No. of logs	Scaling diameter	NHLA lumber grade yields (actual) FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches	*Percent*							
		LOG GRADE 1							
12	13	7.0	7.7	32.8	17.6	0.7	13.1	12.8	8.3
12	14	15.6	7.9	31.2	20.4	—	7.6	13.1	4.2
18	15	25.8	9.4	27.6	19.8	.8	9.4	5.4	1.8
23	16	21.0	7.1	29.1	15.0	1.3	9.6	10.9	6.0
30	17	26.2	8.6	29.4	14.1	1.6	7.6	7.6	4.9
25	18	27.7	7.5	32.7	15.6	.6	7.1	5.5	3.3
14	19	24.7	7.3	35.3	13.1	1.6	4.8	2.9	10.3
15	20	29.8	4.0	40.1	10.4	—	3.2	8.7	3.8
12	21	28.0	6.3	37.6	13.7	—	4.3	8.0	2.1
7	22	28.7	3.0	39.1	12.4	2.3	2.7	2.9	8.9
5	23	44.6	3.9	36.6	9.2	—	3.5	2.2	—
5	24	39.7	8.3	38.8	4.8	—	2.8	2.8	2.8

TABLE 12-18.—*White oak (lowland) lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]—Continued

No. of logs	Scaling diameter	NHLA lumber grade yields (actual) FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches	*Percent*							
		LOG GRADE 2							
4	10	2.6	3.8	20.6	29.6	—	20.2	10.5	12.7
27	11	.9	2.5	18.1	28.0	1.9	20.9	21.8	5.9
48	12	4.3	3.8	24.9	26.6	3.2	13.1	15.9	8.2
50	13	3.2	1.2	26.2	29.9	1.0	15.2	10.7	12.6
50	14	5.5	2.9	29.7	26.6	1.2	11.6	13.9	8.6
61	15	4.5	3.4	30.0	23.3	2.7	13.5	12.7	9.9
40	16	4.8	3.1	36.4	26.6	1.2	9.0	7.7	11.2
38	17	6.6	3.5	30.9	25.0	1.9	10.3	11.0	10.8
35	18	6.8	3.7	40.6	18.3	2.9	6.2	8.2	13.3
17	19	12.2	6.4	35.5	19.6	1.3	9.4	11.3	4.3
8	20	11.8	3.8	43.5	19.4	—	3.3	10.3	7.9
8	21	12.0	1.7	45.6	20.3	1.2	4.8	8.0	5.9
9	22	10.1	3.4	37.5	19.4	5.5	10.4	10.1	3.6
—	23	—	—	—	—	—	—	—	—
4	24	21.0	3.4	41.8	15.6	1.9	2.3	1.9	12.1
		LOG GRADE 3							
1	8	—	8.0	20.0	—	—	52.0	2.0	—
8	9	—	2.9	13.3	21.3	—	33.2	19.6	9.7
25	10	.5	—	17.7	33.3	1.5	14.6	25.6	6.8
16	11	.6	.3	17.7	21.2	3.3	13.9	32.8	10.2
15	12	—	1.2	14.7	27.6	5.7	13.4	18.5	18.9
27	13	.5	.3	13.7	30.5	.4	17.4	23.6	13.6
17	14	—	1.4	8.1	40.4	4.9	12.0	16.0	17.2
20	15	—	—	19.8	24.1	3.3	14.5	21.1	17.2
18	16	1.4	1.3	20.8	30.3	6.6	15.1	9.3	15.2
13	17	.4	.8	14.7	28.3	2.6	9.7	14.0	29.5
11	18	.5	2.9	23.9	33.0	4.4	11.1	13.5	10.7
6	19	—	—	15.3	40.4	8.4	8.6	7.8	19.5
5	20	—	—	17.2	31.0	15.7	10.1	7.1	18.9
5	21	—	1.0	25.1	27.1	1.1	13.6	28.9	3.2
3	22	—	1.6	16.4	46.2	—	7.8	7.1	20.9
1	23	—	—	17.6	37.5	5.6	14.1	8.5	16.7

[1] Lumber graded when green. See text for abbreviations.

TABLE 12-19.—*White oak (upland) lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]

No. of logs	Scaling diameter	NHLA lumber grade yields (actual)							
		FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches				*Percent*				
		LOG GRADE 1							
9	13	15.4	16.2	23.9	13.1	—	5.7	25.7	—
6	14	18.9	4.3	28.8	19.1	—	10.8	18.1	—
5	15	25.6	12.3	20.3	14.3	1.7	6.3	19.5	—
12	16	34.4	10.8	27.2	9.8	—	5.8	10.9	1.1
7	17	29.1	9.2	32.3	4.5	—	3.7	12.0	9.2
4	18	39.2	3.5	18.6	13.4	—	10.6	14.7	—
1	19	13.3	—	36.0	22.2	—	—	28.5	—
8	20	29.7	4.2	36.5	9.5	.4	7.9	11.8	—
14	21	43.2	8.6	25.6	9.8	.6	4.3	7.9	—
8	22	36.4	10.4	29.6	7.0	1.6	3.1	10.2	1.7
7	23	58.8	6.4	16.4	5.3	1.0	5.7	6.4	—
3	24	40.5	6.0	30.2	8.9	—	5.4	4.4	4.6
		LOG GRADE 2							
7	10	3.7	2.7	31.2	17.6	—	14.9	29.9	—
28	11	2.0	4.1	20.9	23.8	2.8	12.4	33.3	.7
46	12	5.6	5.1	23.3	16.8	4.0	12.6	30.8	1.8
27	13	3.3	2.4	26.6	22.8	1.1	11.6	29.4	2.8
29	14	4.4	5.6	25.8	16.6	3.1	12.5	29.5	2.5
32	15	5.5	4.0	31.9	22.5	2.9	6.9	23.3	3.0
18	16	2.4	2.7	30.8	23.3	.6	6.4	30.3	3.5
26	17	6.8	4.3	40.7	19.5	.2	7.8	15.8	4.9
19	18	7.1	5.2	33.5	17.3	3.1	11.0	20.4	2.4
15	19	5.5	3.0	42.1	27.0	.3	8.8	10.5	2.8
8	20	11.7	5.7	35.8	25.8	.6	9.7	7.4	3.3
3	21	23.8	2.7	30.4	20.1	—	6.2	10.0	6.8
5	22	13.9	3.7	41.1	6.2	7.6	5.3	18.8	3.4
3	23	5.6	1.5	48.3	24.7	—	7.6	12.3	—
2	24	16.0	4.2	47.7	15.3	—	7.2	9.6	—

TABLE 12-19.—*White oak (upland) lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]—Continued

No. of logs	Scaling diameter	NHLA lumber grade yields (actual) FAS	Sel	1C	2C	SW	3A	3B	Tmbrs. and SSE
	Inches	*Percent*							
		LOG GRADE 3							
4	8	—	—	2.5	13.7	—	4.3	79.5	—
20	9	.6	—	7.6	18.1	2.6	16.7	54.4	—
22	10	—	—	7.9	16.3	8.6	11.9	53.3	2.0
23	11	—	.5	11.3	19.7	3.7	12.0	50.9	2.1
23	12	1.5	—	7.7	22.9	2.1	9.9	47.6	8.3
17	13	—	—	8.0	20.5	5.9	7.3	55.6	2.7
9	14	1.6	1.7	14.1	24.7	—	10.6	42.1	5.2
14	15	.9	1.7	15.3	25.6	4.8	13.4	33.5	4.8
11	16	—	.7	18.0	27.8	5.6	15.3	24.1	8.5
2	17	—	—	23.8	39.1	—	12.4	24.7	—
7	18	3.9	3.9	21.4	25.0	—	18.7	27.1	—
3	19	—	—	26.4	37.8	—	11.5	24.3	—
4	20	—	3.5	28.2	35.8	—	14.3	18.2	—
1	21	4.0	4.0	45.2	46.8	—	—	—	—
2	22	12.2	8.2	53.4	16.9	—	5.5	3.8	—
—	23	—	—	—	—	—	—	—	—
1	24	3.5	8.1	20.7	34.3	—	6.6	26.8	—

[1] Lumber graded when green. See text for meaning of abbreviations.

TABLE 12-20.—*Sweetgum lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]—Continued

No. of logs	Scaling diameter	NHLA lumber grade yields (actual) FAS	Sel	1C	2C	3A	3B
	Inches	*Percent*					
		LOG GRADE 1					
41	13	21.5	9.7	32.5	26.1	8.4	1.8
42	14	31.0	10.1	28.7	20.1	8.4	1.7
42	15	27.7	9.9	28.7	24.6	8.3	.8
52	16	39.5	8.9	24.6	19.1	5.8	2.1
31	17	36.8	7.2	28.8	20.0	6.0	1.2
29	18	39.1	8.4	26.9	17.3	7.1	1.2
20	19	41.5	7.8	22.9	18.0	6.6	3.2
13	20	38.1	8.5	23.4	20.6	8.2	1.2
7	21	40.0	7.2	33.1	13.2	4.5	2.0
4	22	50.8	7.5	18.7	14.4	6.6	2.0
4	23	34.9	4.2	39.5	14.9	4.4	2.1

Table continued on next page.

TABLE 12-20.—*Sweetgum lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]—Continued

No. of logs	Scaling diameter	FAS	Sel	1C	2C	3A	3B
		NHLA lumber grade yields (actual)					
	Inches	*Percent*					
		LOG GRADE 2					
21	10	1.6	7.6	28.3	41.6	11.8	9.1
66	11	4.5	6.0	24.7	40.1	20.3	4.0
112	12	7.4	7.2	28.1	38.3	13.2	5.8
94	13	10.3	6.0	29.2	35.4	15.0	4.1
89	14	9.4	6.6	32.3	32.9	13.6	5.2
77	15	12.0	5.8	36.2	30.8	12.9	2.3
49	16	10.2	3.8	38.1	34.6	10.9	2.4
30	17	14.0	4.6	40.7	31.6	7.9	1.2
17	18	16.0	3.1	41.0	28.5	7.7	3.7
8	19	23.4	10.4	32.2	23.2	7.0	3.8
4	20	13.6	2.8	28.5	25.6	2.6	26.9
2	21	5.8	—	61.4	16.2	13.1	3.5
—	22	—	—	—	—	—	—
2	23	23.2	4.9	39.2	26.8	5.9	—
		LOG GRADE 3					
2	8	—	—	23.0	55.0	13.0	9.0
40	9	1.3	3.7	10.2	42.1	16.6	26.1
62	10	1.0	1.5	12.7	50.0	25.3	9.5
45	11	—	.6	10.8	49.2	26.2	13.2
41	12	1.0	.9	18.8	47.7	22.4	9.2
36	13	1.6	1.5	18.2	53.5	19.6	5.6
24	14	.9	1.5	21.4	46.1	21.1	9.0
19	15	3.0	1.5	24.9	49.5	14.8	6.3
16	16	4.6	2.2	34.3	42.2	11.1	5.6
6	17	.9	1.0	40.9	42.3	10.1	4.8
8	18	2.8	2.5	25.0	43.7	11.2	14.8
3	19	—	—	38.8	39.0	12.1	10.1
1	20	—	—	25.0	72.8	—	2.2
1	21	7.2	—	39.9	32.7	8.2	12.0

[1] Lumber graded when green. See text for meaning of abbreviations.

TABLE 12-21.—*Yellow-poplar lumber grades related to Forest Service log grades 1, 2, and 3* (Vaughan et al. 1966; Hanks et al. 1980)[1]

No. of logs	Scaling diameter	NHLA lumber grade yields (actual)							
		FAS	Sel	Saps	1C	2A	2B	3A	3B
	Inches	*Percent*							
		LOG GRADE 1							
8	13	—	2.6	8.6	40.1	17.2	18.2	5.0	8.3
10	14	4.1	1.1	25.1	42.4	14.2	6.2	3.8	3.1
5	15	4.8	2.9	3.1	57.0	21.4	1.2	3.6	6.0
7	16	9.1	2.5	24.2	31.4	22.3	7.1	.9	2.5
8	17	11.4	4.6	11.7	42.7	15.3	10.0	2.5	1.8
4	18	1.4	2.1	28.7	50.2	12.6	.8	2.5	1.7
4	19	4.4	3.8	27.3	47.4	9.2	3.3	4.6	—
1	20	15.9	11.1	43.9	22.2	6.9	—	—	—
5	21	21.6	4.1	—	43.9	11.1	16.7	—	2.6
5	22	5.9	—	3.7	63.7	10.9	8.8	2.4	4.6
4	23	31.4	2.0	1.4	45.2	8.6	.9	6.3	4.2
4	24	14.2	1.2	5.5	59.3	15.6	—	.7	3.5
		LOG GRADE 2							
19	10	1.0	1.7	2.6	43.2	24.4	16.8	3.7	6.6
48	11	.8	.2	2.6	33.8	27.1	18.7	10.8	6.0
43	12	—	.2	7.7	34.9	27.8	19.9	6.8	2.7
27	13	1.3	1.8	5.1	34.1	30.1	17.2	7.4	3.0
23	14	.4	1.0	3.9	39.1	30.9	8.3	9.1	7.3
21	15	2.2	.7	10.5	39.8	19.3	18.3	4.6	4.6
9	16	—	.8	—	37.3	35.1	14.9	6.8	5.1
—	17	—	—	—	—	—	—	—	—
6	18	—	—	—	30.7	37.6	12.3	4.1	15.3
4	19	1.5	—	6.9	60.8	16.2	8.7	1.7	4.2
2	20	—	—	.8	46.8	42.4	2.5	7.5	—
3	21	4.7	—	6.6	41.4	23.3	20.2	1.9	1.9
3	22	3.0	—	—	39.9	31.1	16.4	5.9	3.7
—	23	—	—	—	—	—	—	—	—
3	24	8.4	—	—	65.1	17.5	3.1	1.3	4.6
		LOG GRADE 3							
14	8	—	—	1.0	9.0	31.8	42.6	10.5	5.1
33	9	—	—	—	8.1	24.8	36.7	14.7	15.7
30	10	—	—	—	16.6	27.4	29.7	18.6	7.7
17	11	—	—	1.6	15.4	31.5	24.6	16.0	10.9
9	12	—	—	—	26.7	29.7	26.0	10.6	7.0
8	13	—	—	—	21.5	30.2	19.9	9.6	18.8
3	14	—	—	—	4.5	17.4	32.8	29.4	15.9
4	15	—	—	—	23.8	40.9	13.3	13.0	9.0
5	16	—	—	2.9	32.2	31.9	13.9	7.2	11.9
—	17	—	—	—	—	—	—	—	—
1	18	—	—	—	59.0	29.1	—	—	11.9
4	19	5.1	1.0	—	24.6	41.2	17.2	9.2	1.7

[1] Lumber graded when green. See text for meaning of abbreviations.

TABLE 12-22.—*Northern red oak lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Schroeder and Hankes 1967)

Scaling diameter (inches)	Logs	Air-dry lumber grade-yields (curved)						
		FAS	FASIF	Sel	1C	2C	3A	3B
	No.	*Percent*						
		LOG GRADE 1						
13.	12	24	14	5	22	19	15	1
14.	17	24	14	4	25	19	12	2
15.	18	27	14	4	25	18	10	2
16.	22	30	15	4	23	17	9	2
17.	22	34	15	3	22	16	8	2
18.	14	39	14	3	21	14	7	2
19.	16	42	14	3	19	13	7	2
20.	8	45	13	3	19	13	6	1
21.	4	48	13	3	18	11	6	1
22.	5	50	12	3	17	11	6	1
23.	2	53	11	3	16	10	6	1
24.	1	55	11	2	16	9	6	1
		LOG GRADE 2						
10.	8	8	7	5	24	24	25	7
11.	23	6	7	4	25	30	22	6
12.	32	6	7	4	27	31	20	5
13.	28	7	8	4	28	30	18	5
14.	28	9	9	3	29	28	17	5
15.	32	11	9	3	30	27	15	5
16.	16	13	10	3	30	25	14	5
17.	14	16	10	3	30	23	13	5
18.	17	18	11	3	30	21	12	5
19.	3	20	12	3	30	19	11	5
20.	4	23	12	3	30	17	10	5
21.	1	25	13	3	30	16	9	4
22.	1	27	13	3	29	15	9	4
23.	—	29	14	3	29	13	8	4
24.	2	31	14	2	29	13	7	4
		LOG GRADE 3						
8.	23	1	—	2	7	31	40	19
9.	35	1	—	1	8	34	39	17
10.	34	1	1	1	10	36	36	15
11.	30	1	2	1	13	36	33	14
12	26	1	2	1	16	36	31	13
13.	20	1	2	1	20	35	29	12
14.	20	1	3	1	23	34	26	12
15.	9	1	3	1	28	33	23	11
16.	6	1	3	1	33	31	21	10
17.	2	1	3	1	39	29	18	9

[1] See text for meaning of abbreviations.

TABLE 12-23.—*Hickory lumber grades related to Forest Service sawlog grades 1, 2, and 3* (Herrick 1958)[1]

Scaling diameter (inches)	FAS	Sel and 1C	2C	3AC	3BC
	Percent				
	LOG GRADE 1[2]				
14	8	45	28	15	4
16	27	51	12	9	1
18	37	50	6	6	1
20	40	49	4	6	1
22	40	49	4	6	1
24	40	49	4	6	1
	LOG GRADE 2[3]				
12	6	23	19	22	30
14	8	29	20	22	21
16	9	33	21	21	16
18	9	36	24	17	14
20	9	38	25	14	14
22	9	39	27	12	13
24	9	39	29	10	13
	LOG GRADE 3[4]				
8	0	10	12	14	64
10	2	15	23	21	39
12	4	16	32	27	21
14	4	16	39	30	11
16	4	16	43	32	5
18	4	16	46	32	2
20	4	16	47	32	1
22	4	16	49	30	1
24	4	16	50	29	1

[1] Logs harvested in Tennessee Valley Authority area; curved from original data supplied by Paul Lane; lumber graded green. See text for meaning of abbreviations.

[2] Based on six logs.

[3] Based on 35 logs.

[4] Based on 103 logs.

SUBFACTORY CLASS (CONSTRUCTION AND LOCAL USE) LOG GRADES

The **subfactory class** includes logs in both **construction** (specified in table 12-24) and **local use** (specified in table 12-25) classes.

While it is possible to grade products from construction class logs as structural lumber under National Hardwood Lumber Association Rules, or as ties under the rules of the American Railway Engineering Association, no research studies have been conducted to develop log grades based on product recovery within this class. Similarly the local use class has not been subdivided into grades.

Both construction and local use logs are frequently harvested with factory-lumber logs during logging operations and may be sawn for sale by factory lumber grades. Hanks (1973) measured green lumber grade yields for subfactory class hickory, red maple, chestnut oak, red oak sp., white oak, and yellow-poplar logs (tables 12-26 through 12-31), and also for overcup oak (*Quercus lyrata* Walt.), American beech (*Fagus grandifolia* Ehrh.), paper birch *Betula papyrifera* Marsh.), and yellow birch (*Betula alleghaniensis* Britton). Schroeder (1968) provided data on dry lumber grades from red oak sp. subfactory class logs harvested in Illinois—not reproduced here.

For logs to be useful for crosstie production, they must be 12 inches or larger in scaling diameter; even then, only 70 to 84 percent of mill-run hardwood logs are suitable (table 22-18 and 22-24).

Smaller roundwood—down to 6 to 7 inches scaling diameter—can be suitable for sawn mine timbers and round or split mine props. (See table 22-25 for specfications.)

TABLE 12-24.—*Forest Service standard specifications for hardwood construction logs* (Rast et al. 1973)[1]

Statistic	Specification
Position in tree	Butt and upper
Min. diameter, small end	8 inches +
Min. length, without trim	8 feet
Clear cuttings	No requirements.
Sweep allowance, absolute	1/4 diameter small end for each 8 feet of length.
Sound surface defects:	
Single knots	Any number, if no one knot has an average diameter above the callus in excess of 1/3 of log diameter at point of occurrence.
Whorled knots	Any number if sum of knot diameters above the callus does not exceed 1/3 of log diameter at point of occurrence.
Holes	Any number provided none has a diameter over 1/3 of log diameter at point of occurrence, and none extends over 3 inches into included timber.[2]
Unsound surface defects	Same requirements as for sound defects if they extend into included timber.[2] No limit if they do not.
End defects:	
Sound	No requirements.
Unsound	None allowed; log must be sound internally, but will admit 1 shake not to exeed 1/4 the scaling diameter and a longitudinal split not extending over 5 inches into the contained timber.

[1] These specifications are minimum for the class. If, from a group of logs, factory logs are selected first, thus leaving only non-factory logs from which to select construction logs, then the quality range of the construction logs so selected is limited, and the class may be considered a grade. If selection for construction logs is given first priority, then it may be necessary to subdivide the class into grades.

[2] Included timber is always square, and dimension is judged from small end.

TABLE 12-25.—*Suggested specifications for local-use logs* (Rast et al. 1973)

Statistic	Specification
Position in tree	Butt and upper
Min. diameter, small end	8 inches +
Min. length, without trim	8 feet +
Sweep allowance, absolute	1/2 diameter of small end
Max. scale deduction allowed	2/3
Clear cuttings	No requirements
Sound or unsound surface defect limitations	Only requirement is that diameter of knots, holes, rot, etc. shall not exceed 1/2 diameter of log at point of occurrence.
Sound end defects	No requirements

TABLE 12-26.—*Hickory lumber grade yields from construction and local-use class logs* (Hanks 1973)[1,2]

Diameter (inches)	Lumber grade			
	FAS	1C	2C	3C
	Percent			
8	0	0	26	74
9	0	0	38	62
10	0	0	47	53
11	0	1	52	47
12	0	3	55	42
13	0	6	53	41
14	0	10	49	41
15	0	16	40	44
16	0	22	29	49

[1] Logs meeting specifications for factory grade 3 or better have been excluded.

[2] Lumber graded green according to rules of the National Hardwood Lumber Association (1974).

TABLE 12-27.—*Red maple lumber grade yields from construction and local-use class logs* (Hanks 1973)[1,2]

Diameter (inches)	Lumber grade							
	FAS	FASIF	SEL	1C	2A	2B	3A	3B
	Percent							
8	0	0	0	1	1	56	0	42
9	0	0	0	2	5	69	5	19
10	0	0	0	2	8	75	11	4
11	0	0	0	4	11	72	13	0
12	0	0	0	6	13	65	15	1
13	0	0	0	9	14	50	14	13
14	0	0	0	12	14	28	11	35
15	0	0	0	16	14	0	5	65

[1] Logs meeting specifications for factory grade 3 or better have been excluded.
[2] Lumber graded green according to rules of the National Hardwood Lumber Association (1974).

TABLE 12-28.—*Chestnut oak lumber grade yields from construction and local-use class logs* (Hanks 1973)[1,2]

Diameter (inches)	Lumber grade							
	FAS	FASIF	SEL	1C	2C	SW	3A	3B
	Percent							
8	0	0	0	0	3	22	22	53
9	0	0	0	1	5	24	22	48
10	0	0	0	1	7	26	23	43
11	0	0	0	1	9	28	23	39
12	0	0	0	2	11	30	22	35
13	0	0	0	2	12	32	22	32
14	0	0	0	3	13	34	21	29
15	0	0	0	4	13	35	21	27
16	0	0	0	5	14	37	19	25
17	0	0	0	6	14	38	18	24
18	0	0	0	7	13	40	16	24
19	0	0	0	9	12	41	14	24
20	0	0	0	10	11	42	12	25
21	0	0	0	12	10	43	9	26
22	0	0	0	14	8	44	7	27
23	0	0	0	15	6	45	4	30

[1] Logs meeting specifications for factory grade 3 or better have been excluded.
[2] Lumber graded green according to rules of the National Hardwood Lumber Association (1974).

TABLE 12-29.—*Red oak*[1] *lumber grade yields from construction and local-use class logs* (Hanks 1973)[2,3]

Diameter (inches)	Lumber grade					
	FAS	Sel	1C	2C	3A	3B
	Percent					
9	0	0	0	2	21	77
10	0	0	2	6	22	70
11	0	0	3	10	23	64
12	0	0	5	14	24	57
13	0	1	7	17	25	50
14	0	1	10	20	25	44
15	0	1	12	23	25	39
16	1	1	15	25	25	33
17	1	1	18	27	25	28
18	1	2	21	29	24	23
19	1	2	24	30	24	19

[1] Includes black, northern red, and scarlet oaks.

[2] Lumber graded green according to rules of the National Hardwood Lumber Association (1974).

[3] Logs meeting factory grade 3 or better have been excluded.

TABLE 12-30.—*White oak lumber grade yields from construction and local-use class logs* (Hanks 1973)[1 2]

Diameter (inches)	Lumber grade							
	FAS	FASIF	SEL	1C	2C	SW	3A	3B
	Percent							
8	0	0	0	0	6	16	38	40
9	0	0	0	0	9	18	37	36
10	0	0	0	2	11	20	35	32
11	0	0	0	5	13	21	33	28
12	0	0	1	7	14	23	31	24
13	0	0	1	9	16	24	29	21
14	0	0	1	11	17	25	28	18
15	0	0	0	13	18	27	26	16
16	0	0	0	15	19	28	24	14
17	0	1	0	16	19	29	22	13
18	0	1	0	18	19	30	21	11
19	0	1	0	19	20	31	19	10
20	0	1	0	20	20	32	18	9
21	0	1	0	21	19	33	16	10
22	0	1	0	22	18	34	15	10
23	0	1	0	22	18	34	14	11
24	0	1	0	23	17	35	12	12

[1] Logs meeting specifications for factory grade 3 or better have been excluded.

[2] Lumber graded green according to rules of the National Hardwood Lumber Association (1974).

TABLE 12-31.—*Yellow-poplar lumber grade yields from subfactory class construction and local-use class logs* (Hanks 1973)[1]

Diameter (inches)	Lumber grade						
	FAS	SEL	SAPS	1C	2A	2B	3C
	Percent						
8	0	0	0	2	7	89	2
9	0	0	0	3	14	81	2
10	0	0	0	5	21	72	2
11	0	0	0	7	27	64	2
12	0	0	0	9	32	57	2
13	0	0	1	12	35	50	2
14	0	0	1	15	38	44	2
15	0	0	2	18	39	39	2
16	0	0	2	22	39	35	2
17	0	0	2	26	39	31	2
18	0	0	3	30	37	28	2
19	0	0	4	35	34	25	2
20	0	0	5	40	30	23	2

[1] Lumber graded green according to rules of the National Hardwood Lumber Association (1974).

SAWBOLT GRADES

Many hardwood trees are of low quality because of small diameter, crookedness, or the occurrence of grade reducing defects on the stem. These trees frequently contain sections shorter than saw log length (8 feet) which are of high quality and can be processed into short lumber or turning squares for the furniture industry. Lower quality sawbolts can be profitably processed on high production mills to produce pallet parts.

Research to develop bolt grades based on lumber recovery has been hampered by the lack of a standard grading system for short lumber. Some short lumber grading systems have been recommended (Bingham and Schroeder 1976; Reynolds and Schroeder 1977), but they have not been widely used.

An alternative method to using lumber grade-yield as the basis for developing bolt grades is to use the yield of furniture cuttings or turning squares of specified quality (Dunmire et al. 1972; Dunmire et al. 1974; Huffman 1973; Kroon 1974; Landt 1974abcd).

Square-foot yields of clear-one-face cuttings from low-quality yellow-poplar bolts are given in equations 18-35, 18-36, and 18-37. Similar data for red maple are given in equations 18-38, 18-39, and 18-40. Table 18-64 gives board foot yields of 4/4 kiln-dried, clear-one-face cuttings from bolts of five grades, six diameters, and three species.

Rast (1971) developed a preliminary grading system for 4-, 5-, and 6-foot white oak bolts based on the yield of Clear One Face and Better (ClF&B) furniture cuttings (table 12-32). Grade 1 bolts yielded over 65 percent of their volume in ClF&B cuttings, Grade 2 bolts yielded 46 to 65 percent, and Grade 3 bolts yielded 25 to 45 percent of their volume in ClF&B cuttings (table 12-33).

Yield of pallet boards (proportion of green log weight) obtained by Reynolds (1974) from short low-grade hardwood logs is tabulated in discussion related to figure 18-114 and 18-115.

Calvert (1955) found that percent of bolt volume (inside bark) recovered as 4/4 lumber from white ash bolts varied from 42 percent for 4-inch bolts to 57 percent for 16-inch bolts. Percentage of white ash tree volume converted to clear cuttings was independent of tree dbh, in the range from 8 to 20 inches, and averaged about 34 percent of volume inside bark to a 4-inch top. The proportions of clear cuttings in sawn lumber from white ash bolts were 69 percent for 8-inch trees, 65 percent for 14-inch trees, and 63 percent for 20-inch tree.

For additional data see subsections BOLT SAWING PATTERNS and BOLTERS in Section 18-11 (SAWMILL LAYOUTS FOR SHORT, SMALL, HARDWOOD LOGS).

TABLE 12-32.—*Grading specifications for white oak saw bolts* (Rast 1971[1])

Grading factors	Bolt grade		
	B-1	B-2	B-3
Bolt, length, feet	4 to 6	4 to 6	4 to 6
Minimum bolt diameter at small end inside bark, inches	10 if 5 or 6 feet long 12 if 4 feet long	8	6
Quality of bolt faces ...	No defects[2] allowed on any face	[3]	No restrictions on number of defects

[1] Bolts of all three grades must be straight, sound, and with mimimal end defects.

[2] Low bumps and light bark distortions not considered defects.

[3] For bolt grade B-2 the three best faces must be at least 50 percent clear, the clear area contained in a maximum of two cuttings with minimum length of 2 feet.

TABLE 12-33.—*Volume, and percent of total bolt volume, of clear-one-face (C1F) and better furniture cuttings from graded white oak bolts of three lengths and several diameters* (Rast 1971)[1]

Diameter (inches)	4 feet		5 feet		6 feet	
	Volume in C1F	Percent of total volume	Volume in C1F	Percent of total volume	Volume in C1F	Percent of total volume
	Bd. ft.	*Percent*	*Bd. ft.*	*Percent*	*Bd. ft.*	*Percent*
	GRADE 1					
10	—	—	14	78	16	73
11	—	—	17	77	20	74
12	16	76	20	74	24	73
13	19	76	23	72	28	74
	GRADE 2					
8	4	44	6	55	7	50
9	6	55	8	57	10	56
10	8	57	10	56	13	59
11	10	56	13	59	16	59
12	12	57	16	59	20	61
13	15	60	20	63	24	63
14	18	62	23	62	28	62
	GRADE 3					
6	2	50	2	33	3	43
7	2	33	3	37	4	40
8	3	33	4	36	5	36
9	4	36	6	43	7	39
10	6	43	7	39	9	41
11	7	39	9	41	11	41

[1] See table 12-32 for grade definitions.

12-8 HARDWOOD TREE GRADES[6]

HARDWOOD TREE GRADES FOR FACTORY LUMBER

Early applications of the U.S. Forest Service hardwood sawlog grades included efforts to grade each log in standing trees. This approach was time consuming and inaccurate due to difficulty of estimating clear cutting lengths on the surface of upper logs.

Subsequently, tree grades were developed based on the grade of an indicator section of the tree, usually the butt 16-foot log or a portion of it (Campbell 1951, 1959; Herrick and Jackson 1957; Hyvarinen 1968; Lucas 1969; Marden 1965; Schroeder 1964). These grading systems were usually applicable to only one species. They established the correlation of total tree lumber grade yield with: (1) tree size as measured by diameter at breast height (dbh) and merchantable height to the end of sawlog utilization; and (2) the grade of the indicator section. In most of these studies tree lumber grade yields were estimated for the logs in the trees on the basis of previous log grade studies—trees were not sawed nor was the lumber graded.

In 1971 a set of interim specifications for hardwood tree grades for factory lumber was accepted by the U.S. Forest Service (Hanks 1971). Further research was conducted to add additional species and, in 1976, the hardwood tree grades for factory lumber were accepted as the standard Forest Service hardwood tree grading system (table 12-34). This grading system is based on actual sawmill recovery studies in which lumber grade yield and volume was tallied for over 2,200 trees of 11 species, six of which are important where southern pines grow, as follows:

Species	Table
Maple, red	12-35ABC
Oak, black	12-36ABC
Oak, chestnut	12-37ABC
Oak, northern red	12-38ABC
Oak, white	12-39ABC
Yellow-poplar	12-40ABC

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[6] This section, with some editorial changes and with addition of tabular data on lumber grade volume in hardwood trees of three grades and six species that occur where southern pines grow, is taken from Schroeder (1981) by permission of the author and the Forest Products Research Society.

In addition to these six species, the source reference (Hanks 1976a) includes data on basswood (*Tilia americana* L.), yellow birch (*Betula alleghaniensis* Britton), paper birch (*Betula papyrifera* Marsh.), black cherry (*Prunus serotina* Ehrh.), and sugar maple (*Acer saccharum* Marsh.).

Keys to abbreviations used in tables 12-35 through 12-40 for lumber grades of the National Hardwood Lumber Association are as follows:

FAS = Firsts and seconds
FASIF = Firsts and seconds one face
Sel = Select
1C = No. 1 Common
2C = No. 2 Common
2A = No. 2A Common, yellow-poplar only
2B = No. 2B Common, yellow-poplar only
3A = No. 3A Common
3B = No. 3B Common

TABLE 12-34.—*Hardwood tree grades for factory lumber* (Hanks 1976a)

Grade factor	Tree grade 1	Tree grade 2	Tree grade 3
Length of grading zone, feet	Butt 16	Butt 16	Butt 16
Length of grading section[1], feet	Best 12	Best 12	Best 12
Dbh, minimum, inches	16[2]	13	10
Diameter, minimum inside bark at top of grading section, inches	13[2] 16 20	11[3] 12	8
Clear cuttings (on the 3 best faces)[4]:			
Length, minimum, feet	7 5 3	3 3	2
Number on face (maximum)	2	2 3	[5]
Yield in face length (minimum)	5/6	4/6	3/6
Cull deduction, including crook and sweep but excluding shake, maximum within grading section, percent	9	9[6]	50

[1] Whenever a 14- or 16-foot section of the butt 16-foot log is better than the best 12-foot section, the grade of the longer section will become the grade of the tree. This longer section, when used, is the basis for determining the grading factors such as diameter and cull deduction.

[2] In basswood and ash, dib at top of grading section must be at least 12 inches and dbh must be at least 15 inches.

[3] Grade 2 trees can be 10 inches dib at top of grading section if otherwise meeting surface requirements for small grade 1s.

[4] A clear cutting is a portion of a face free of defects, extending the width of the face. A face is one-fourth of the surface of the grading section as divided lengthwise.

[5] Unlimited.

[6] Fifteen percent crook and sweep or 40 percent total cull deduction are permitted in grade 2 if size and surface of grading section qualify as grade 1. If rot shortens the required clear cuttings to the extent of dropping the butt log to grade 2, do not drop the tree's grade to 3 unless the cull deduction for rot is greater than 40 percent.

TABLE 12-35A.—*Red maple lumber grade volume in 2-, 3-, and 4-log grade-1 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2A	2B	3A	3B
	Board feet							
	2 LOGS							
16	29.2	21.6	11.3	26.2	36.1	42.7	14.6	2.9
17	32.4	26.3	11.2	34.8	41.1	42.7	14.6	4.0
18	35.8	31.3	11.2	44.0	46.3	42.7	14.6	5.1
19	39.5	36.5	11.1	53.7	51.9	42.7	14.6	6.3
20	43.3	42.1	11.1	63.8	57.7	42.7	14.6	7.6
21	47.3	48.0	11.0	74.6	63.9	42.7	14.6	8.9
22	51.5	54.1	11.0	85.8	70.4	42.7	14.6	10.3
23	55.9	60.5	10.9	97.5	77.1	42.7	14.6	11.7
24	60.5	67.2	10.9	109.8	84.2	42.7	14.6	13.3
25	65.3	74.2	10.8	122.6	91.6	42.7	14.6	14.9
26	70.3	81.5	10.7	136.0	99.2	42.7	14.6	16.5
	3 LOGS							
16	31.3	37.7	12.2	34.8	55.6	52.4	23.5	10.2
17	41.4	41.9	13.7	43.3	59.5	52.4	23.5	11.3
18	52.1	46.3	15.3	52.4	63.5	52.4	23.5	12.5
19	63.5	51.0	17.0	62.0	67.8	52.4	23.5	13.8
20	75.5	56.0	18.8	72.1	72.4	52.4	23.5	15.2
21	88.1	61.2	20.6	82.8	77.1	52.4	23.5	16.6
22	101.3	66.6	22.6	93.9	82.1	52.4	23.5	18.1
23	115.1	72.3	24.6	105.6	87.3	52.4	23.5	19.6
24	129.5	78.3	26.8	117.8	92.8	52.4	23.5	21.3
25	144.6	84.5	29.0	130.5	98.5	52.4	23.5	22.9
26	160.2	90.9	31.4	143.8	104.4	52.4	23.5	24.7
	4 LOGS							
16	33.3	53.9	13.1	43.3	75.2	62.2	32.3	17.4
17	50.4	57.6	16.1	51.8	77.9	62.2	32.3	18.7
18	68.4	61.4	19.4	60.8	80.8	62.2	32.3	19.9
19	87.5	65.5	22.8	70.4	83.8	62.2	32.3	21.3
20	107.7	69.8	26.4	80.4	87.0	62.2	32.3	22.7
21	128.8	74.4	30.2	91.0	90.3	62.2	32.3	24.3
22	151.0	79.1	34.2	102.1	93.8	62.2	32.3	25.8
23	174.2	84.1	38.4	113.7	97.5	62.2	32.3	27.5
24	198.5	89.3	42.7	125.8	101.4	62.2	32.3	29.2
25	223.8	94.7	47.3	138.4	105.4	62.2	32.3	31.0
26	250.1	100.3	52.0	151.6	109.6	62.2	32.3	32.9

[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long. See text for meaning of abbreviations.

TABLE 12-35B.—*Red maple lumber grade volume in 2-, 2½-, and 3-log grade-2 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2A	2B	3A	3B
	Board feet							
			2 LOGS					
13	5.6	12.4	7.8	14.4	38.7	44.1	10.5	0.0
14	8.4	14.6	8.1	20.0	41.7	44.4	11.4	.9
15	11.4	16.9	8.4	26.0	44.9	44.6	12.5	3.5
16	14.7	19.4	8.8	32.4	48.3	44.8	13.6	6.3
17	18.1	22.0	9.2	39.2	51.9	45.1	14.7	9.3
18	21.7	24.8	9.6	46.4	55.8	45.4	16.0	12.4
19	25.5	27.8	10.0	54.1	59.9	45.7	17.3	15.8
20	29.6	30.9	10.5	62.1	64.1	46.0	18.7	19.3
21	33.8	34.2	11.0	70.6	68.7	46.4	20.1	23.0
22	38.2	37.6	11.5	79.4	73.4	46.7	21.6	26.9
23	42.9	41.2	12.0	88.7	78.3	47.1	23.2	30.9
24	47.8	45.0	12.6	98.4	83.5	47.5	24.9	35.1
			2½ LOGS					
13	2.9	11.3	8.6	17.8	53.1	49.7	13.0	0.6
14	7.7	14.8	9.2	23.3	55.1	49.9	14.0	2.8
15	12.9	18.5	9.8	29.2	57.2	50.1	15.0	5.2
16	18.4	22.4	10.4	35.6	59.5	50.4	16.1	7.7
17	24.3	26.7	11.1	42.3	61.9	50.7	17.2	10.4
18	30.5	31.1	11.8	49.4	64.4	50.9	18.5	13.2
19	37.1	35.9	12.5	57.0	67.1	51.2	19.8	16.3
20	44.1	40.9	13.3	64.9	69.9	51.6	21.2	19.4
21	51.4	46.1	14.1	73.3	72.9	51.9	22.6	22.8
22	59.1	51.6	15.0	82.0	76.0	52.3	24.2	26.3
23	67.2	57.4	15.9	91.2	79.3	52.6	25.8	29.9
24	75.5	63.4	16.8	100.8	82.7	53.0	27.4	33.7
			3 LOGS					
13	0.1	10.2	9.5	21.2	67.5	55.2	15.5	2.8
14	6.9	14.9	10.3	26.7	68.5	55.4	16.5	4.7
15	14.3	20.0	11.1	32.5	69.5	55.7	17.5	6.9
16	22.1	25.5	12.0	38.7	70.6	55.9	18.6	9.1
17	30.5	31.3	12.9	45.4	71.8	56.2	19.8	11.5
18	39.4	37.5	13.9	52.4	73.0	56.5	21.0	14.0
19	48.8	44.0	15.0	59.9	74.3	56.8	22.3	16.7
20	58.7	50.8	16.1	67.7	75.7	57.1	23.7	19.6
21	69.1	58.1	17.3	76.0	77.2	57.4	25.2	22.5
22	80.0	65.6	18.5	84.6	78.7	57.8	26.7	25.7
23	91.4	73.5	19.8	93.7	80.3	58.2	28.3	28.9
24	103.3	81.8	21.1	103.1	81.9	58.6	29.9	32.3

[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long. See text for meaning of abbreviations.

TABLE 12-35C.—*Red maple lumber grade volume in 1-, 2-, and 3-log grade-3 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2A	2B	3A	3B
	Board feet							
	1 LOG							
10	0.0	0.1	0.0	0.0	3.8	18.9	4.7	1.9
11	.5	.3	.0	3.7	5.9	19.5	5.8	2.9
12	1.2	.6	.1	8.0	8.3	20.1	7.0	4.0
13	2.0	.8	.6	12.7	10.9	20.7	8.3	5.1
14	2.9	1.1	1.2	17.8	13.7	21.4	9.8	6.4
15	3.8	1.5	1.9	23.2	16.7	22.2	11.3	7.8
16	4.8	1.8	2.6	29.0	19.9	23.0	12.9	9.3
17	5.8	2.2	3.3	35.2	23.3	23.9	14.6	10.8
18	6.9	2.6	4.1	41.8	26.9	24.8	16.4	12.5
19	8.1	3.0	4.9	48.8	30.7	25.8	18.4	14.3
20	9.4	3.4	5.8	56.1	34.8	26.8	20.4	16.1
	2 LOGS							
10	0.1	0.5	4.2	1.7	18.5	45.8	7.0	1.9
11	.8	1.8	4.5	5.6	21.5	46.4	8.1	2.9
12	1.5	3.1	4.8	9.9	24.9	47.0	9.4	4.0
13	2.3	4.6	5.1	14.6	28.5	47.6	10.8	5.1
14	3.1	6.1	5.4	19.7	32.5	48.4	12.3	6.4
15	4.1	7.8	5.8	25.1	36.7	49.1	13.9	7.8
16	5.0	9.7	6.2	31.0	41.2	49.9	15.7	9.3
17	6.1	11.6	6.7	37.2	46.0	50.8	17.5	10.8
18	7.2	13.6	7.1	43.7	51.1	51.7	19.5	12.5
19	8.4	15.8	7.6	50.7	56.5	52.7	21.5	14.3
20	9.6	18.1	8.1	58.0	62.1	53.7	23.7	16.1
	3 LOGS							
10	0.3	1.0	9.3	3.6	33.2	72.7	9.2	1.9
11	1.0	3.2	9.4	7.5	37.2	73.3	10.4	2.9
12	1.7	5.6	9.5	11.9	41.5	73.9	11.8	4.0
13	2.5	8.3	9.6	16.6	46.2	74.6	13.3	5.1
14	3.4	11.2	9.7	21.6	51.2	75.3	14.9	6.4
15	4.3	14.2	9.8	27.1	56.7	76.0	16.6	7.8
16	5.3	17.5	9.9	32.9	62.5	76.8	18.4	9.3
17	6.3	21.0	10.0	39.1	68.7	77.7	20.4	10.8
18	7.5	24.7	10.2	45.7	75.3	78.6	22.5	12.5
19	8.6	28.6	10.3	52.6	82.2	79.6	24.7	14.3
20	9.9	32.8	10.4	60.0	89.5	80.6	27.0	16.1

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[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long. See text for meaning of abbreviations.

TABLE 12-36A.—*Black oak lumber grade volume in 2-, 3-, and 3½-log, grade-1 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2C	SW[2]	3A	3B
	Board feet							
	2 LOGS							
16	0.0	16.7	1.9	36.4	41.8	12.2	52.4	17.2
17	.0	20.1	2.9	46.0	45.3	12.2	53.2	18.0
18	4.4	23.7	3.9	56.3	49.1	12.2	54.0	18.8
19	11.8	27.6	5.0	67.1	53.0	12.2	54.9	19.6
20	19.6	31.7	6.2	78.5	57.2	12.2	55.8	20.5
21	27.7	35.9	7.4	90.5	61.6	12.2	56.8	21.4
22	36.3	40.4	8.7	103.1	66.2	12.2	57.8	22.4
23	45.2	45.1	10.0	116.2	71.0	12.2	58.9	23.4
24	54.6	50.0	11.4	130.0	76.0	12.2	60.0	24.5
25	64.3	55.1	12.8	144.3	81.3	12.2	61.2	25.6
26	74.5	60.4	14.3	159.3	86.7	12.2	62.4	26.7
	3 LOGS							
16	0.0	11.7	1.9	54.2	77.0	20.9	76.5	53.7
17	6.8	16.9	2.9	66.8	80.5	20.9	77.3	54.5
18	14.9	22.4	3.9	80.2	84.3	20.9	78.2	55.3
19	23.4	28.1	5.0	94.3	88.2	20.9	79.0	56.1
20	32.5	34.2	6.2	109.2	92.4	20.9	80.0	57.0
21	41.9	40.6	7.4	124.9	96.8	20.9	81.0	57.9
22	51.9	47.3	8.7	141.3	101.4	20.9	82.0	58.9
23	62.3	54.4	10.0	158.5	106.2	20.9	83.1	59.9
24	73.1	61.7	11.4	176.5	111.3	20.9	84.2	61.0
25	84.5	69.4	12.8	195.2	116.5	20.9	85.4	62.1
26	96.3	77.3	14.3	214.7	122.0	20.9	86.6	63.3
27	108.5	85.6	15.9	235.0	127.7	20.9	87.8	64.5
28	121.2	94.2	17.5	256.0	133.5	20.9	89.2	65.7
29	134.4	103.1	19.2	277.8	139.6	20.9	90.5	67.0
30	148.0	112.3	21.0	300.3	146.0	20.9	91.9	68.3
31	162.1	121.9	22.8	323.6	152.5	20.9	93.4	69.7
32	176.7	131.7	24.6	347.7	159.2	20.9	94.9	71.1
33	191.7	141.8	26.6	372.6	166.2	20.9	96.5	72.6
34	207.2	152.3	28.5	398.2	173.4	20.9	98.1	74.1

TABLE 12-36A.—*Black oak lumber grade volume in 2-, 3-, and 3½-log, grade-1 trees* (Hanks 1976a)[1]—Continued

Dbh (inches)	FAS	FASIF	Sel	1C	2C	SW[2]	3A	3B
	Board feet							
	3½ LOGS							
16	3.3	9.3	1.9	63.1	94.6	25.3	88.6	72.0
17	11.5	15.3	2.9	77.2	98.1	25.3	89.4	72.7
18	20.1	21.7	3.9	92.1	101.9	25.3	90.2	73.5
19	29.3	28.4	5.0	107.9	105.9	25.3	91.1	74.4
20	38.9	35.5	6.2	124.6	110.0	25.3	92.1	75.3
21	49.0	43.0	7.4	142.1	114.4	25.3	93.0	76.2
22	59.7	50.8	8.7	160.4	119.0	25.3	94.1	77.2
23	70.8	59.0	10.0	179.7	123.8	25.3	95.1	78.2
24	82.4	67.6	11.4	199.7	128.9	25.3	96.3	79.2
25	94.5	76.5	12.8	220.7	134.1	25.3	97.4	80.4
26	107.2	85.8	14.3	242.4	139.6	25.3	98.7	81.5
27	120.3	95.5	15.9	265.1	145.3	25.3	99.9	82.7
28	133.9	105.5	17.5	288.5	151.2	25.3	101.2	84.0
29	148.0	115.9	19.2	312.9	157.3	25.3	102.6	85.3
30	162.5	126.6	21.0	338.1	163.6	25.3	104.0	86.6
31	177.6	137.7	22.8	364.1	170.1	25.3	105.5	88.0
32	193.2	149.2	24.6	391.0	176.9	25.3	107.0	89.4
33	209.3	161.1	26.6	418.8	183.8	25.3	108.5	90.9
34	225.9	173.3	28.5	447.4	191.0	25.3	110.1	92.4

[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974).

[2] SW means sound wormy. See text for meaning of other abbreviations.

TABLE 12-36B.—*Black oak lumber grade volume in 1½-, 2-, and 3-log, grade-2 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2C	SW[2]	3A	3B
	Board feet							
	1½ LOGS							
13	0.0	3.3	0.0	0.0	18.4	1.5	29.2	28.2
14	1.9	5.9	.0	.0	22.0	1.5	30.2	27.4
15	4.8	8.6	.0	7.7	25.9	1.5	31.2	26.4
16	7.9	11.6	.0	19.5	30.1	1.5	32.3	25.5
17	11.2	14.8	.2	31.9	34.5	1.5	33.5	24.4
18	14.7	18.1	.8	45.2	39.2	1.5	34.7	23.3
19	18.4	21.7	1.5	59.2	44.1	1.5	36.0	22.1
20	22.3	25.4	2.2	73.9	49.3	1.5	37.4	20.9
21	26.4	29.4	2.9	89.4	54.8	1.5	38.8	19.6
22	30.7	33.5	3.6	105.7	60.6	1.5	40.3	18.2
23	35.2	37.8	4.4	122.7	66.6	1.5	41.9	16.8
24	39.9	42.3	5.3	140.5	72.9	1.5	43.6	15.3

Table continued on next page.

TABLE 12-36B.—*Black oak lumber grade volume in 1½-, 2-, and 3-log, grade-2 trees* (Hanks 1976a)[1]—Continued

Dbh (inches)	FAS	FASIF	Sel	1C	2C	SW[2]	3A	3B
	Board feet							
			2 LOGS					
13	0.0	1.5	0.7	0.0	24.9	6.6	38.2	36.6
14	1.9	4.3	1.1	4.2	29.6	6.6	39.5	35.8
15	4.8	7.4	1.5	15.9	34.6	6.6	40.9	35.1
16	7.9	10.7	1.9	28.5	40.0	6.6	42.4	34.3
17	11.2	14.2	2.3	41.8	45.8	6.6	44.0	33.4
18	14.7	17.9	2.7	56.0	51.8	6.6	45.6	32.5
19	18.4	21.9	3.2	70.9	58.3	6.6	47.4	31.5
20	22.3	26.0	3.7	86.7	65.1	6.6	49.3	30.5
21	26.4	30.4	4.3	103.3	72.2	6.6	51.2	29.4
22	30.7	34.9	4.8	120.6	79.7	6.6	53.3	28.3
23	35.2	39.7	5.4	138.8	87.5	6.6	55.4	27.1
24	39.9	44.7	6.0	157.8	95.7	6.6	57.7	25.8
25	44.7	49.9	6.7	177.6	104.2	6.6	60.0	24.6
26	49.8	55.3	7.3	198.3	113.1	6.6	62.5	23.2
27	55.1	60.9	8.0	219.7	122.3	6.6	65.0	21.8
28	60.6	66.8	8.7	241.9	131.9	6.6	67.6	20.4
			3 LOGS					
13	0.0	0.0	6.0	6.8	37.8	16.6	56.2	53.3
14	1.9	1.3	6.1	19.1	44.7	16.6	58.1	52.8
15	4.8	5.0	6.2	32.3	52.0	16.6	60.3	52.4
16	7.9	8.9	6.3	46.5	59.9	16.6	62.5	51.9
17	11.2	13.1	6.4	61.5	68.3	16.6	64.9	51.4
18	14.7	17.5	6.6	77.5	77.2	16.6	67.5	50.8
19	18.4	22.2	6.7	94.4	86.6	16.6	70.2	50.3
20	22.3	27.1	6.9	112.2	96.5	16.6	73.0	49.7
21	26.4	32.3	7.0	130.9	107.0	16.6	76.0	49.0
22	30.7	37.7	7.2	150.5	117.9	16.6	79.2	48.4
23	35.2	43.4	7.4	171.1	129.4	16.6	82.5	47.7
24	39.9	49.4	7.5	192.5	141.3	16.6	85.9	46.9
25	44.7	55.6	7.7	214.9	153.8	16.6	89.5	46.2
26	49.8	62.0	7.9	238.1	166.7	16.6	93.2	45.4
27	55.1	68.7	8.1	262.3	180.2	16.6	97.0	44.5
28	60.6	75.7	8.3	287.4	194.2	16.6	101.1	43.7
29	66.3	82.9	8.6	313.4	208.7	16.6	105.2	42.8
30	72.2	90.4	8.8	340.4	223.7	16.6	109.5	41.9

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[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long.

[2] SW means sound wormy. See text for meaning of other abbreviations.

TABLE 12-36C.—*Black oak lumber grade volume in 1-, 2-, and 2½-log, grade-3 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2C	SW[2]	3A	3B
	Board feet							
	1 LOG							
10	0.0	0.0	1.0	0.0	1.6	3.5	9.2	14.5
11	.0	.0	1.0	.0	4.7	4.0	12.1	12.0
12	.2	.0	.9	5.5	8.1	4.7	15.4	9.3
13	.6	1.6	.9	12.7	11.7	5.3	18.9	6.3
14	1.1	3.6	.9	20.4	15.7	6.0	22.7	3.1
15	1.5	5.8	.8	28.7	20.0	6.8	26.7	.0
16	2.0	8.1	.8	37.6	24.5	7.6	31.1	.0
	2 LOGS							
12	0.0	0.0	0.0	5.5	28.1	13.2	35.4	42.5
13	.2	1.6	.2	12.7	31.7	13.4	37.2	42.3
14	1.3	3.6	.5	20.4	35.6	13.5	39.1	42.0
15	2.6	5.8	.8	28.7	39.8	13.7	41.1	41.8
16	3.9	8.1	1.2	37.6	44.2	13.9	43.3	41.5
17	5.3	10.5	1.6	47.1	49.0	14.2	45.7	41.2
18	6.8	13.2	2.0	57.1	54.0	14.4	48.1	40.8
19	8.4	15.9	2.4	67.8	59.4	14.7	50.8	40.5
20	10.0	18.8	2.9	78.9	65.0	14.9	53.5	40.1
21	11.8	21.9	3.4	90.7	70.9	15.2	56.4	39.7
22	13.6	25.1	3.9	103.1	77.1	15.5	59.5	39.3
23	15.5	28.5	4.4	116.0	83.6	15.8	62.7	38.9
24	17.5	32.0	5.0	129.5	90.4	16.1	66.0	38.4
	2½ LOGS							
16	4.8	8.1	1.4	37.6	54.1	17.1	49.5	64.2
17	6.7	10.5	2.0	47.1	58.8	17.0	50.6	65.7
18	8.6	13.2	2.7	57.1	63.8	16.9	51.9	67.2
19	10.7	15.9	3.3	67.8	69.1	16.8	53.2	68.9
20	12.9	18.8	4.1	78.9	74.6	16.6	54.6	70.6
21	15.2	21.9	4.8	90.7	80.5	16.5	56.1	72.5
22	17.6	25.1	5.6	103.1	86.6	16.4	57.7	74.4
23	20.1	28.5	6.4	116.0	93.0	16.3	59.3	76.4
24	22.7	32.0	7.3	129.5	99.7	16.1	61.0	78.5
25	25.5	35.6	8.2	143.5	106.7	16.0	62.7	80.7
26	28.3	39.5	9.1	158.2	114.0	15.8	64.6	83.0
27	31.3	43.4	10.1	173.4	121.5	15.6	66.5	85.4
28	34.3	47.5	11.1	189.2	129.3	15.5	68.5	87.8

[1] Based on U.S. Forest Service tree grades; lumber graded green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long. See text for meaning of abbreviations.

[2] SW means sound wormy. See text for meaning of other abbreviations.

TABLE 12-37A.—*Chestnut oak lumber grade volume in 1½-, 2-, and 3-log, grade-1 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FAS WHND[2]	FASIF	FASIF WHND	Sel	Sel WHND	1C	1C WHND	2C	SW[3]	3A	3B
	Board feet											
	1½ LOGS											
16	6.8	0.0	3.2	2.8	3.2	1.3	18.1	7.3	28.8	15.1	20.0	15.3
17	7.7	2.2	4.9	4.0	3.2	1.3	21.2	12.9	28.2	16.1	22.7	22.4
18	8.6	6.9	6.7	5.4	3.2	1.3	24.4	18.9	27.6	17.1	25.4	30.0
19	9.5	11.8	8.6	6.8	3.2	1.3	27.8	25.2	26.9	18.2	28.4	38.0
20	10.6	17.0	10.6	8.3	3.2	1.3	31.4	31.8	26.1	19.3	31.5	46.4
21	11.6	22.5	12.7	9.9	3.2	1.3	35.2	38.8	25.4	20.5	34.8	55.3
22	12.7	28.2	14.8	11.6	3.2	1.3	39.2	46.1	24.6	21.8	38.2	64.5
23	13.9	34.2	17.1	13.3	3.2	1.3	43.4	53.7	23.7	23.1	41.8	74.3
24	15.1	40.4	19.5	15.1	3.2	1.3	47.7	61.7	22.9	24.5	45.5	84.4
	2 LOGS											
16	6.0	5.3	6.1	2.8	3.2	1.3	19.4	11.1	30.0	27.7	24.0	15.3
17	7.6	9.7	7.8	4.0	3.2	1.3	23.0	17.5	29.9	29.0	26.6	22.4
18	9.4	14.4	9.6	5.4	3.2	1.3	26.8	24.3	29.8	30.2	29.4	30.0
19	11.3	19.3	11.5	6.8	3.2	1.3	30.8	31.4	29.7	31.6	32.3	38.0
20	13.2	24.5	13.5	8.3	3.2	1.3	35.0	39.0	29.6	33.0	35.4	46.4
21	15.3	29.9	15.6	9.9	3.2	1.3	39.5	46.9	29.5	34.5	38.7	55.3
22	17.5	35.6	17.8	11.6	3.2	1.3	44.2	55.2	29.4	36.1	42.1	64.5
23	19.7	41.6	20.1	13.3	3.2	1.3	49.0	63.9	29.3	37.7	45.7	74.3
24	22.1	47.8	22.5	15.1	3.2	1.3	54.1	73.0	29.2	39.4	49.4	84.4
25	24.6	54.3	25.0	17.0	3.2	1.3	59.5	82.5	29.0	41.2	53.3	95.0
26	27.2	61.1	27.6	19.0	3.2	1.3	65.0	92.4	28.9	43.1	57.4	106.0
27	29.8	68.1	30.3	21.0	3.2	1.3	70.7	102.6	28.8	45.0	61.6	117.5

TABLE 12-37A.—*Chestnut oak lumber grade volume in 1½-, 2-, and 3-log, grade-1 trees* (Hanks 1976a)[1]—Continued

Dbh (inches)	FAS	FAS WHND[2]	FASIF	FASIF WHND	Sel	Sel WHND	1C	1C WHND	2C	SW[3]	3A	3B
	Board feet											
					3 LOGS							
16	4.2	20.4	12.0	2.8	3.2	1.3	22.0	18.7	32.2	53.0	31.9	15.3
17	7.5	24.7	13.7	4.0	3.2	1.3	26.7	26.7	33.2	54.7	34.5	22.4
18	11.0	29.3	15.5	5.4	3.2	1.3	31.6	35.1	34.2	56.5	37.3	30.0
19	14.7	34.2	17.3	6.8	3.2	1.3	36.8	44.0	35.3	58.4	40.2	38.0
20	18.6	39.4	19.3	8.3	3.2	1.3	42.3	53.3	36.5	60.4	43.3	46.4
21	22.7	44.8	21.4	9.9	3.2	1.3	48.0	63.2	37.7	62.5	46.6	55.3
22	27.0	50.5	23.6	11.6	3.2	1.3	54.1	73.5	39.0	64.7	50.0	64.5
23	31.5	56.4	25.9	13.3	3.2	1.3	60.4	84.3	40.4	67.0	53.6	74.3
24	36.2	62.6	28.3	15.1	3.2	1.3	67.0	95.6	41.8	69.4	57.3	84.4
25	41.1	69.1	30.8	17.0	3.2	1.3	73.9	107.3	43.2	71.9	61.2	95.0
26	46.2	75.8	33.4	19.0	3.2	1.3	81.1	119.6	44.7	74.6	65.3	106.0
27	51.5	82.8	36.1	21.0	3.2	1.3	88.6	132.3	46.3	77.3	69.5	117.5

[1] Based on U.S. Forest Service log grades; lumber graded green according to rules of the National Hardwood Lumber Association (1974). A two-log tree contains two logs each nominally 16 feet long.

[2] WHND means worm holes no defect.

[3] SW means sound wormy. See text for meaning of other abbreviations.

TABLE 12-37B.—*Chestnut oak lumber grade volume in 1-, 2-, and 3-log, grade-2 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FAS WHND[2]	FASIF	FASIF WHND	Sel	Sel WHND	1C	1C WHND	2C	SW[3]	3A	3B
	Board feet											
					1 LOG							
13	0.0	0.0	0.0	4.6	9.0	0.0	17.9	2.6	7.0	0.0	26.9	4.3
14	.0	.0	.4	4.7	8.1	.0	17.3	6.0	7.8	.0	26.7	9.0
15	.0	1.2	1.6	4.9	7.2	.0	16.7	9.7	8.6	.3	26.4	13.9
16	.0	5.3	2.9	5.0	6.2	.0	16.0	13.7	9.5	1.1	26.2	19.2
17	.0	9.6	4.3	5.2	5.1	.0	15.3	17.9	10.4	2.0	25.9	24.9
18	.0	14.3	5.8	5.4	3.9	.0	14.5	22.3	11.4	3.0	25.6	30.9
19	.0	19.1	7.4	5.6	2.7	.0	13.7	27.0	12.4	3.9	25.3	37.3
20	.0	24.3	9.1	5.8	1.5	.3	12.8	31.9	13.5	5.0	24.9	44.0
21	.0	29.7	10.8	6.1	.2	.5	11.9	37.1	14.7	6.1	24.5	51.0
22	.0	35.4	12.7	6.3	.0	.8	11.0	42.6	15.9	7.2	24.2	58.4
					2 LOGS							
13	3.1	0.0	0.0	0.3	4.3	0.0	16.0	1.1	17.9	24.6	31.1	14.8
14	3.1	.0	.4	1.1	4.1	.0	16.3	6.3	18.4	25.4	31.7	19.4
15	3.0	1.2	1.6	1.9	3.9	.0	16.6	11.7	18.9	26.1	32.5	24.4
16	3.0	5.3	2.9	2.9	3.7	.2	16.9	17.6	19.4	27.0	33.2	29.7
17	3.0	9.6	4.3	3.8	3.4	.4	17.2	23.9	20.0	27.8	34.1	35.3
18	2.9	14.3	5.8	4.9	3.2	.6	17.6	30.5	20.6	28.8	34.9	41.3
19	2.9	19.1	7.4	6.0	2.9	.8	18.0	37.5	21.3	29.8	35.9	47.7
20	2.8	24.3	9.1	7.1	2.6	1.0	18.4	44.9	22.0	30.8	36.8	54.4
21	2.8	29.7	10.8	8.3	2.3	1.3	18.8	52.6	22.7	31.9	37.9	61.4
22	2.7	35.4	12.7	9.6	1.9	1.5	19.3	60.8	23.5	33.0	38.9	68.8
23	2.7	41.3	14.6	10.9	1.6	1.8	19.7	69.3	24.3	34.2	40.0	76.5
24	2.6	47.5	16.6	12.3	1.2	2.1	20.2	78.2	25.1	35.5	41.2	84.6
25	2.6	54.0	18.7	13.7	.9	2.3	20.7	87.5	26.0	36.8	42.4	93.0

TABLE 12-37B.—*Chestnut oak lumber grade volume in 1-, 2-, and 3-log, grade-2 trees* (Hanks 1976a)[1]—Continued

Dbh (inches)	FAS	FAS WHND[2]	FASIF	FASIF WHND	Sel	Sel WHND	1C	1C WHND	2C	SW[3]	3A	3B
	Board feet											
26	2.5	60.7	20.9	15.2	.5	2.6	21.3	97.1	26.9	38.2	43.7	101.7
27	2.5	67.7	23.1	16.8	.1	3.0	21.8	107.2	27.8	39.6	45.0	110.8
28	2.4	75.0	25.5	18.4	.0	3.3	22.4	117.6	28.8	41.0	46.4	120.3
29	2.4	82.5	27.9	20.1	.0	3.6	23.0	128.4	29.8	42.6	47.8	130.0
30	2.3	90.3	30.4	21.8	.0	4.0	23.6	139.5	30.8	44.1	49.3	140.2
					3 LOGS							
13	6.2	0.0	0.0	0.0	0.0	0.6	14.1	0.0	28.8	50.5	35.2	25.2
14	6.2	.0	.4	.0	.2	.7	15.2	6.5	29.0	51.2	36.8	29.8
15	6.2	1.2	1.6	.0	.7	.9	16.5	13.8	29.2	52.0	38.5	34.8
16	6.2	5.3	2.9	.7	1.2	1.0	17.8	21.6	29.4	52.8	40.3	40.1
17	6.2	9.6	4.3	2.4	1.8	1.2	19.2	29.9	29.6	53.7	42.2	45.8
18	6.2	14.3	5.8	4.3	2.4	1.4	20.7	38.7	29.9	54.6	44.3	51.8
19	6.2	19.1	7.4	6.3	3.0	1.6	22.3	48.0	30.2	55.6	46.5	58.1
20	6.2	24.3	9.1	8.4	3.7	1.8	23.9	57.8	30.4	56.6	48.8	64.8
21	6.2	29.7	10.8	10.5	4.4	2.0	25.7	68.1	30.7	57.7	51.2	71.8
22	6.2	35.4	12.7	12.8	5.1	2.2	27.5	79.0	31.0	58.9	53.7	79.2
23	6.2	41.3	14.6	15.2	5.9	2.5	29.5	90.3	31.4	60.1	56.3	86.9

Table continued next page.

TABLE 12-37B.—*Chestnut oak lumber grade volume in 1-, 2-, and 3-log, grade-2 trees* (Hanks 1976a)[1]—Continued

Dbh (inches)	FAS	FAS WHND[2]	FASIF	FASIF WHND	Sel	Sel WHND	1C	1C WHND	2C	SW[3]	3A	3B
	Board feet											
24	6.2	47.5	16.6	17.7	6.7	2.7	31.5	102.1	31.7	61.3	59.1	95.0
25	6.2	54.0	18.7	20.3	7.5	3.0	33.6	114.5	32.1	62.6	61.9	103.4
26	6.1	60.7	20.9	23.1	8.4	3.2	35.7	127.3	32.4	64.0	64.9	112.2
27	6.1	67.7	23.1	25.9	9.3	3.5	38.0	140.6	32.8	65.4	68.0	121.3
28	6.1	75.0	25.5	28.8	10.3	3.8	40.4	154.5	33.2	66.9	71.3	130.7
29	6.1	82.5	27.9	31.9	11.2	4.1	42.8	168.8	33.6	68.4	74.6	140.5
30	6.1	90.3	30.4	35.0	12.3	4.4	45.3	183.7	34.0	70.0	78.1	150.6

[1] Based on U.S. Forest Service log grades; lumber graded green according to rules of the National Hardwood Lumber Association (1974). A two-log tree contains two logs each nominally 16 feet long.

[2] WHND means worm holes no defect.

[3] SW means sound wormy. See text for meaning of other abbreviations.

TABLE 12-37C.—*Chestnut oak lumber grade volume in 1-, 2-, and 3-log, grade-3 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FAS WHND[2]	FASIF	FASIF WHND	Sel	Sel WHND	1C	1C WHND	2C	SW[3]	3A	3B
	Board feet											
					1 LOG							
10	0.0	0.0	0.0	0.0	1.1	0.4	4.1	3.3	2.4	5.4	4.4	10.3
11	.0	.0	.0	.0	1.1	.4	3.6	5.2	3.1	5.8	5.7	12.5
12	.0	.0	.1	.0	1.1	.4	3.0	7.2	3.8	6.1	7.2	15.0
13	.0	1.0	.2	.0	1.1	.4	2.3	9.3	4.6	6.5	8.8	17.6
14	.0	2.2	.3	.0	1.1	.4	1.6	11.7	5.4	7.0	10.5	20.4
15	.0	3.4	.4	.0	1.1	.4	.8	14.2	6.3	7.4	12.3	23.5
16	.0	4.8	.5	.3	1.1	.4	.0	16.9	7.3	7.9	14.3	26.8
17	.0	6.3	.7	.8	1.1	.4	.0	19.8	8.3	8.5	16.3	30.2
18	.0	7.8	.8	1.3	1.1	.4	.0	22.8	9.4	9.0	18.6	33.9
19	.0	9.4	1.0	1.8	1.1	.4	.0	26.0	10.5	9.6	20.9	37.8
20	.0	11.2	1.1	2.4	1.1	.4	.0	29.4	11.7	10.3	23.4	41.9
					2 LOGS							
10	0.0	0.0	0.0	0.0	1.1	0.4	4.1	0.0	8.5	16.7	22.0	8.5
11	.0	.0	.0	.0	1.1	.4	4.7	.0	9.1	18.2	23.2	13.4
12	.0	.0	.0	.0	1.1	.4	5.5	.0	9.9	19.8	24.5	18.7
13	.0	1.0	.1	.1	1.1	.4	6.3	3.6	10.6	21.6	25.9	24.5
14	.0	2.2	.3	.5	1.1	.4	7.2	8.0	11.5	23.6	27.4	30.8
15	.0	3.4	.6	.9	1.1	.4	8.2	12.8	12.4	25.7	29.0	37.5
16	.0	4.8	.9	1.4	1.1	.4	9.2	17.9	13.3	27.9	30.7	44.7
17	.0	6.3	1.2	1.8	1.1	.4	10.3	23.4	14.4	30.3	32.5	52.4
18	.0	7.8	1.5	2.3	1.1	.4	11.4	29.2	15.4	32.8	34.4	60.5
19	.0	9.4	1.8	2.9	1.1	.4	12.6	35.3	16.6	35.5	36.5	69.1

Table continued on next page.

TABLE 12-37C.—*Chestnut oak lumber grade volume in 1-, 2-, and 3-log, grade-3 trees* (Hanks 1976a)[1]—Continued

Dbh (inches)	FAS	FAS WHND[2]	FASIF	FASIF WHND	Sel	Sel WHND	1C	1C WHND	2C	SW[3]	3A	3B
	Board feet											
20	.0	11.2	2.1	3.5	1.1	.4	13.9	41.7	17.8	38.3	38.7	78.2
21	.0	13.0	2.5	4.0	1.1	.4	15.2	48.5	19.1	41.3	40.9	87.7
22	.0	14.9	2.9	4.7	1.1	.4	16.6	55.6	20.4	44.4	43.3	97.7
23	.0	16.9	3.3	5.3	1.1	.4	18.1	63.0	21.8	47.7	45.8	108.1
24	.0	18.9	3.7	6.0	1.1	.4	19.7	70.8	23.2	51.1	48.4	119.0
25	.0	21.1	4.1	6.7	1.1	.4	21.3	78.8	24.8	54.6	51.1	130.4
26	.0	23.4	4.6	7.5	1.1	.4	22.9	87.3	26.3	58.3	54.0	142.2
					3 LOGS							
12	0.0	0.0	0.0	0.8	1.1	0.4	8.0	0.0	15.9	33.5	41.8	22.5
13	.0	1.0	.0	1.1	1.1	.4	10.3	.0	16.7	36.7	42.9	31.5
14	.0	2.2	.4	1.5	1.1	.4	12.8	4.4	17.5	40.2	44.2	41.2
15	.0	3.4	.8	2.0	1.1	.4	15.5	11.5	18.4	43.9	45.6	51.6
16	.0	4.8	1.2	2.4	1.1	.4	18.4	19.0	19.4	47.9	47.1	62.7
17	.0	6.3	1.6	2.9	1.1	.4	21.4	27.0	20.4	52.2	48.7	74.6
18	.0	7.8	2.1	3.4	1.1	.4	24.6	35.5	21.5	56.7	50.3	87.1
19	.0	9.4	2.6	3.9	1.1	.4	28.0	44.5	22.6	61.4	52.1	100.4
20	.0	11.2	3.2	4.5	1.1	.4	31.6	54.0	23.8	66.4	54.0	114.4

[1] Based on U.S. Forest Service log grades; lumber graded green according to rules of the National Hardwood Lumber Association (1974). A two-log tree contains two logs each nominally 16 feet long.

[2] WHND means worm holes no defect.

[3] SW means sound wormy. See text for meaning of abbreviations.

TABLE 12-38A.—*Northern red oak lumber grade volume in 2-, 3-, and 4-log, grade-1 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2C	3A	3B
	Board feet						
		2 LOGS					
16.	15.6	10.1	6.9	46.1	60.4	37.0	3.8
17.	25.5	14.0	7.4	55.8	62.9	37.4	5.0
18.	35.9	18.1	7.9	66.1	65.5	37.8	6.2
19.	47.0	22.4	8.5	77.0	68.3	38.2	7.6
20.	58.6	27.0	9.1	88.5	71.3	38.6	9.0
21.	70.9	31.8	9.7	100.5	74.3	39.1	10.5
22.	83.7	36.8	10.4	113.2	77.6	39.6	12.0
23.	97.2	42.1	11.1	126.4	81.0	40.1	13.7
24.	111.2	47.6	11.8	140.2	84.5	40.7	15.3
25.	125.9	53.4	12.5	154.7	88.2	41.2	17.1
26.	141.1	59.3	13.3	169.7	92.0	41.8	19.0
27.	156.9	65.6	14.1	185.3	96.0	42.4	20.9
28.	173.4	72.0	15.0	201.4	100.2	43.1	22.9
29.	190.4	78.7	15.9	218.2	104.5	43.7	24.9
30.	208.0	85.6	16.8	235.6	108.9	44.4	27.0
31.	226.2	92.8	17.7	253.5	113.5	45.1	29.3
32.	245.1	100.1	18.7	272.1	118.3	45.8	31.5
33.	264.5	107.8	19.7	291.2	123.2	46.6	33.9
34.	284.5	115.6	20.7	310.9	128.2	47.3	36.3
35.	305.1	123.7	21.8	331.2	133.4	48.1	38.8
		3 LOGS					
16.	11.7	23.0	5.6	41.2	116.5	36.2	7.1
17.	24.3	28.3	6.7	55.8	118.6	37.5	8.5
18.	37.6	34.0	7.8	71.4	120.7	38.9	10.0
19.	51.7	40.0	9.0	87.8	123.0	40.4	11.6
20.	66.6	46.4	10.2	105.1	125.4	42.0	13.3
21.	82.3	53.0	11.5	123.3	127.9	43.7	15.0
22.	98.7	60.0	12.8	142.4	130.5	45.4	16.8
23.	115.8	67.3	14.3	162.4	133.3	47.2	18.7
24.	133.8	74.9	15.8	183.2	136.1	49.1	20.7
25.	152.5	82.9	17.3	205.0	139.1	51.1	22.8
26.	171.9	91.1	18.9	227.6	142.2	53.1	25.0
27.	192.2	99.7	20.6	251.1	145.5	55.2	27.2
28.	213.1	108.7	22.3	275.6	148.9	57.4	29.6
29.	234.9	117.9	24.1	300.9	152.3	59.7	32.0
30.	257.4	127.5	26.0	327.1	156.0	62.1	34.5
31.	280.7	137.4	27.9	354.1	159.7	64.6	37.1
32.	304.7	147.6	29.9	382.1	163.5	67.1	39.8
33.	329.5	158.2	32.0	411.0	167.5	69.7	42.5
34.	355.1	169.0	34.1	440.7	171.6	72.4	45.4
35.	381.4	180.2	36.3	471.3	175.8	75.2	48.3

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[1] Table continued on next page.

TABLE 12-38A.—*Northern red oak lumber grade volume in 2-, 3-, and 4-log, grade-1 trees* (Hanks 1976a)[1]—Continued

Dbh (inches)	FAS	FASIF	Sel	1C	2C	3A	3B
	Board feet						
		4 LOGS					
20	74.6	65.7	11.3	121.7	179.5	45.4	17.5
21	93.6	74.2	13.3	146.1	181.4	48.2	19.5
22	113.6	83.1	15.3	171.6	183.4	51.2	21.6
23	134.5	92.5	17.5	198.3	185.5	54.3	23.8
24	156.3	102.2	19.7	226.2	187.7	57.5	26.1
25	179.1	112.4	22.1	255.3	190.0	60.9	28.5
26	202.8	122.9	24.5	285.6	192.4	64.4	31.0
27	227.4	133.9	27.1	317.0	194.9	68.1	33.6
28	252.9	145.3	29.7	349.7	197.5	71.8	36.3
29	279.4	157.1	32.4	383.5	200.2	75.8	39.0
30	306.8	169.4	35.3	418.5	203.0	79.8	41.9
31	335.1	182.0	38.2	454.7	205.9	84.1	44.9
32	364.4	195.1	41.2	492.1	208.8	88.4	48.0
33	394.6	208.6	44.3	530.7	211.9	92.9	51.2
34	425.7	222.5	47.5	570.5	215.0	97.5	54.4
35	457.7	236.8	50.8	611.4	218.3	102.3	57.8

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[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long. See text for meaning of abbreviations.

TABLE 12-38B.—*Northern red oak lumber grade volume in 1½-, 2-, and 3-log, grade-2 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2C	3A	3B
	Board feet						
		1½ LOGS					
13	0.0	18.3	3.7	11.3	22.2	12.9	5.7
14	.0	19.0	3.7	17.5	25.5	14.7	6.1
15	.0	19.8	3.7	24.1	29.0	16.6	6.5
16	1.0	20.6	3.7	31.1	32.7	18.7	7.0
17	5.0	21.4	3.7	38.6	36.7	20.9	7.5
18	9.3	22.3	3.7	46.6	40.9	23.3	8.0
19	13.8	23.3	3.7	55.0	45.4	25.8	8.6
20	18.6	24.3	3.7	63.9	50.1	28.4	9.2
21	23.6	25.3	3.7	73.2	55.1	31.1	9.8
22	28.8	26.5	3.7	83.0	60.3	34.0	10.4
23	34.3	27.6	3.7	93.3	65.7	37.1	11.1
24	40.1	28.8	3.7	104.0	71.4	40.2	11.8
25	46.1	30.1	3.7	115.1	77.3	43.5	12.6
26	52.3	31.4	3.7	126.8	83.5	46.9	13.3
27	58.8	32.8	3.7	138.8	89.9	50.5	14.1
28	65.5	34.2	3.7	151.3	96.5	54.2	15.0
29	72.4	35.7	3.7	164.3	103.4	58.0	15.8
30	79.6	37.2	3.7	177.8	110.5	62.0	16.7
		2 LOGS					
13	0.0	15.5	3.7	16.3	43.1	28.8	6.5
14	1.3	17.0	3.7	24.3	46.5	30.2	7.1
15	4.8	18.6	3.7	33.0	50.2	31.6	7.7
16	8.6	20.4	3.7	42.2	54.2	33.2	8.4
17	12.7	22.3	3.7	52.1	58.4	34.9	9.1
18	16.9	24.2	3.7	62.5	62.9	36.6	9.8
19	21.4	26.3	3.7	73.6	67.6	38.5	10.6
20	26.2	28.5	3.7	85.2	72.6	40.4	11.4
21	31.2	30.8	3.7	97.5	77.8	42.5	12.2
22	36.5	33.3	3.7	110.3	83.3	44.6	13.1
23	42.0	35.8	3.7	123.7	89.1	46.9	14.1
24	47.7	38.5	3.7	137.8	95.1	49.3	15.1
25	53.7	41.2	3.7	152.4	101.4	51.7	16.1
26	59.9	44.1	3.7	167.6	107.9	54.3	17.2
27	66.4	47.1	3.7	183.4	114.7	56.9	18.3
28	73.1	50.2	3.7	199.9	121.7	59.7	19.4
29	80.1	53.4	3.7	216.9	129.0	62.6	20.6
30	87.3	56.8	3.7	234.5	136.5	65.5	21.8

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[1] Table continued on next page.

TABLE 12-38B.—*Northern red oak lumber grade volume in 1½-, 2-, and 3-log, grade-2 trees* (Hanks 1976a)[1]—Continued

Dbh (inches)	FAS	FASIF	Sel	1C	2C	3A	3B
	Board feet						
		3 LOGS					
18	32.2	28.1	3.7	94.4	106.8	63.3	13.3
19	36.7	32.4	3.7	110.7	112.0	63.9	14.5
20	41.5	37.0	3.7	127.8	117.6	64.5	15.8
21	46.5	41.8	3.7	145.9	123.4	65.1	17.1
22	51.7	46.9	3.7	164.8	129.5	65.8	18.5
23	57.2	52.2	3.7	184.6	135.9	66.6	20.0
24	63.0	57.8	3.7	205.3	142.5	67.3	21.6
25	69.0	63.5	3.7	226.9	149.5	68.1	23.1
26	75.2	69.5	3.7	249.3	156.7	68.9	24.8
27	81.7	75.8	3.7	272.7	164.2	69.8	26.5
28	88.4	82.3	3.7	296.9	172.0	70.7	28.3
29	95.4	89.0	3.7	322.0	180.1	71.6	30.2
30	102.6	95.9	3.7	347.9	188.5	72.6	32.1
31	110.0	103.1	3.7	374.8	197.2	73.5	34.1
32	117.7	110.5	3.7	402.5	206.1	74.6	36.2
33	125.6	118.2	3.7	431.1	215.3	75.6	38.3
34	133.8	126.1	3.7	460.6	224.8	76.7	40.5
35	142.3	134.2	3.7	491.0	234.6	77.8	42.7

[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long. See text for meaning of abbreviations.

TABLE 12-38C.—*Northern red oak lumber grade volume in 1-, 2-, and 3-log, grade-3 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2C	3A	3B
	Board feet						
		1 LOG					
10.	1.1	0.0	2.0	0.0	4.7	13.9	9.1
11.	1.1	.0	2.0	2.1	9.4	15.4	9.9
12.	1.2	.2	2.0	7.0	14.5	17.2	10.8
13.	1.3	1.1	2.0	12.3	20.1	19.1	11.7
14.	1.3	2.1	2.0	18.0	26.1	21.1	12.7
15.	1.4	3.1	2.0	24.2	32.6	23.3	13.8
16.	1.5	4.2	2.0	30.8	39.5	25.7	15.0
		2 LOGS					
10.	0.0	0.0	2.0	0.0	8.7	33.3	26.6
11.	.0	.5	2.0	1.8	13.5	35.2	28.1
12.	.0	1.5	2.0	6.8	18.8	37.2	29.9
13.	.3	2.6	2.0	12.4	24.6	39.4	31.7
14.	1.1	3.8	2.0	18.3	30.8	41.7	33.8
15.	1.9	5.1	2.0	24.7	37.4	44.3	35.9
16.	2.8	6.5	2.0	31.5	44.6	47.0	38.3
17.	3.7	7.9	2.0	38.8	52.2	49.9	40.7
18.	4.6	9.5	2.0	46.5	60.2	52.9	43.4
19.	5.7	11.1	2.0	54.7	68.7	56.2	46.1
20.	6.8	12.8	2.0	63.3	77.7	59.6	49.0
21.	7.9	14.7	2.0	72.3	87.1	63.2	52.1
22.	9.1	16.6	2.0	81.8	97.0	67.0	55.3
23.	10.4	18.6	2.0	91.7	107.3	70.9	58.7
24.	11.7	20.6	2.0	102.1	118.1	75.0	62.2
25.	13.0	22.8	2.0	112.9	129.4	79.3	65.9
		3 LOGS					
16.	4.0	8.7	2.0	32.2	49.6	68.3	61.5
17.	5.8	10.4	2.0	39.8	57.4	71.6	65.2
18.	7.6	12.2	2.0	47.7	65.7	75.1	69.2
19.	9.6	14.2	2.0	56.1	74.4	78.7	73.3
20.	11.6	16.2	2.0	65.0	83.6	82.6	77.7
21.	13.8	18.4	2.0	74.4	93.3	86.7	82.3
22.	16.0	20.6	2.0	84.1	103.5	91.0	87.1
23.	18.4	23.0	2.0	94.4	114.1	95.5	92.2
24.	20.9	25.4	2.0	105.1	125.2	100.1	97.5
25.	23.5	28.0	2.0	116.3	136.8	105.0	103.0

[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long. See text for meaning of abbreviations.

TABLE 12-39A.—*White oak lumber grade volume in 2-, 3-, and 4-log, grade-1 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2C	SW[2]	3A	3B
	Board feet							
	2 LOGS							
16	9.1	9.9	1.2	28.0	34.2	7.4	31.6	26.2
17	13.9	13.6	2.4	35.9	40.4	8.1	34.0	26.9
18	18.9	17.5	3.6	44.3	47.1	8.9	36.5	27.7
19	24.3	21.7	4.8	53.2	54.1	9.7	39.2	28.5
20	30.0	26.0	6.2	62.6	61.5	10.5	42.1	29.3
21	35.9	30.6	7.6	72.4	69.3	11.4	45.1	30.2
22	42.2	35.4	9.1	82.7	77.5	12.4	48.2	31.1
23	48.7	40.4	10.6	93.6	86.0	13.4	51.5	32.1
24	55.6	45.7	12.2	104.8	95.0	14.4	54.9	33.1
25	62.7	51.2	13.9	116.6	104.3	15.4	58.5	34.1
26	70.1	56.9	15.7	128.9	114.0	16.5	62.2	35.2
	3 LOGS							
16	9.1	9.9	6.6	13.3	66.5	11.6	55.8	33.5
17	13.9	13.6	7.5	28.5	74.3	14.6	57.5	34.6
18	18.9	17.5	8.4	44.6	82.5	17.7	59.3	35.7
19	24.3	21.7	9.4	61.7	91.2	21.1	61.3	37.0
20	30.0	26.0	10.4	79.6	100.4	24.6	63.3	38.3
21	35.9	30.6	11.5	98.5	110.0	28.3	65.5	39.6
22	42.2	35.4	12.7	118.3	120.1	32.2	67.7	41.0
23	48.7	40.4	13.9	139.0	130.7	36.3	70.1	42.5
24	55.6	45.7	15.1	160.6	141.8	40.5	72.6	44.1
25	62.7	51.2	16.4	183.2	153.3	44.9	75.2	45.7
26	70.1	56.9	17.8	206.6	165.3	49.5	77.8	47.4
27	77.8	62.8	19.2	231.0	177.8	54.3	80.6	49.2
28	85.8	69.0	20.7	256.4	190.7	59.3	83.5	51.0
	4 LOGS							
16	9.1	9.9	12.0	0.0	98.8	15.7	79.9	40.8
17	13.9	13.6	12.6	21.1	108.1	21.0	81.0	42.3
18	18.9	17.5	13.3	44.9	117.9	26.6	82.1	43.8
19	24.3	21.7	14.0	70.1	128.3	32.4	83.3	45.5
20	30.0	26.0	14.7	96.6	139.2	38.6	84.6	47.2
21	35.9	30.6	15.5	124.5	150.7	45.2	85.9	49.1
22	42.2	35.4	16.3	153.8	162.8	52.0	87.3	51.0
23	48.7	40.4	17.1	184.4	175.4	59.2	88.8	53.0
24	55.6	45.7	18.0	216.4	188.6	66.6	90.3	55.1
25	62.7	51.2	19.0	249.7	202.3	74.4	91.9	57.3
26	70.1	56.9	19.9	284.4	216.6	82.5	93.5	59.6
27	77.8	62.8	20.9	320.5	231.5	91.0	95.2	62.0
28	85.8	69.0	22.0	357.9	246.9	99.7	97.0	64.4
29	94.1	75.3	23.1	396.7	262.9	108.8	98.9	67.0
30	102.6	81.9	24.2	436.8	279.5	118.2	100.8	69.6

[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long.

[2] SW means sound wormy. See text for meaning of other abbreviations.

TABLE 12-39B.—*White oak lumber grade volume in 1-, 2-, and 3-log, grade-2 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2C	SW[2]	3A	3B
	Board feet							
	1 LOG							
13	1.6	3.8	3.9	0.0	3.8	0.0	16.6	18.4
14	2.7	5.2	3.9	.0	7.9	.0	17.4	18.4
15	4.0	6.8	3.9	4.5	12.2	.0	18.3	18.4
16	5.4	8.5	3.9	14.9	16.9	.0	19.2	18.4
17	6.8	10.3	3.9	25.9	21.9	.0	20.2	18.4
18	8.4	12.2	3.9	37.6	27.1	.0	21.3	18.4
19	10.0	14.2	3.9	50.0	32.7	2.2	22.4	18.4
20	11.7	16.3	3.9	63.0	38.5	4.7	23.6	18.4
	2 LOGS							
13	1.6	3.8	3.9	0.0	16.1	9.8	25.6	31.3
14	2.7	5.2	3.9	4.8	23.0	11.5	27.8	31.3
15	4.0	6.8	3.9	15.0	30.3	13.3	30.1	31.3
16	5.4	8.5	3.9	26.0	38.1	15.3	32.6	31.3
17	6.8	10.3	3.9	37.7	46.5	17.4	35.3	31.3
18	8.4	12.2	3.9	50.1	55.4	19.7	38.1	31.3
19	10.0	14.2	3.9	63.3	64.7	22.0	41.1	31.3
20	11.7	16.3	3.9	77.1	74.6	24.5	44.3	31.3
21	13.6	18.5	3.9	91.6	85.0	27.1	47.6	31.3
22	15.4	20.9	3.9	106.9	95.9	29.8	51.0	31.3
23	17.4	23.3	3.9	122.8	107.3	32.7	54.7	31.3
24	19.5	25.9	3.9	139.5	119.2	35.7	58.5	31.3
25	21.7	28.5	3.9	156.8	131.6	38.8	62.4	31.3
	3 LOGS							
13	1.6	3.8	3.9	4.6	28.4	29.5	34.6	44.1
14	2.7	5.2	3.9	14.7	38.0	31.2	38.2	44.1
15	4.0	6.8	3.9	25.6	48.4	33.1	42.0	44.1
16	5.4	8.5	3.9	37.2	59.4	35.1	46.0	44.1
17	6.8	10.3	3.9	49.6	71.1	37.2	50.4	44.1
18	8.4	12.2	3.9	62.7	83.6	39.4	55.0	44.1
19	10.0	14.2	3.9	76.6	96.8	41.8	59.8	44.1
20	11.7	16.3	3.9	91.2	110.7	44.3	64.9	44.1
21	13.6	18.5	3.9	106.5	125.3	47.0	70.3	44.1
22	15.4	20.9	3.9	122.7	140.6	49.7	75.9	44.1
23	17.4	23.3	3.9	139.5	156.6	52.6	81.9	44.1
24	19.5	25.9	3.9	157.1	173.3	55.6	88.0	44.1
25	21.7	28.5	3.9	175.5	190.8	58.8	94.4	44.1
26	23.9	31.3	3.9	194.6	208.9	62.1	101.1	44.1

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[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long.

[2] SW means sound wormy. See text for meaning of other abbreviations.

TABLE 12-39C.—*White oak lumber grade volume in 1-, 2-, and 3-log grade-3 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	FASIF	Sel	1C	2C	SW[2]	3A	3B
	Board feet							
		1 LOG						
10	0.0	0.0	0.3	12.9	5.9	0.0	3.4	12.4
11	.0	.0	.3	15.4	8.9	.0	5.4	13.0
12	.0	.6	.3	18.0	12.3	.0	7.6	13.7
13	.6	1.2	.3	20.9	15.9	1.0	9.9	14.4
14	1.2	1.9	.3	24.0	19.8	2.4	12.4	15.2
15	1.9	2.6	.3	27.4	24.0	3.9	15.2	16.0
16	2.5	3.3	.3	31.0	28.5	5.6	18.1	17.0
17	3.3	4.1	.3	34.8	33.3	7.4	21.1	17.9
18	4.1	5.0	.3	38.8	38.4	9.2	24.4	18.9
19	4.9	5.9	.3	43.1	43.7	11.2	27.9	20.0
20	5.8	6.8	.3	47.6	49.4	13.3	31.5	21.1
21	6.7	7.8	.3	52.4	55.3	15.5	35.4	22.3
22	7.7	8.8	.3	57.4	61.6	17.8	39.4	23.6
		2 LOGS						
10	0.0	0.0	1.3	0.0	4.8	3.1	18.4	38.9
11	.0	.0	1.3	.0	10.3	5.1	20.5	39.4
12	.0	.6	1.3	.0	16.2	7.2	22.8	39.8
13	.6	1.2	1.3	1.8	22.7	9.6	25.3	40.3
14	1.2	1.9	1.3	8.0	29.7	12.1	28.0	40.9
15	1.9	2.6	1.3	14.8	37.2	14.8	31.0	41.5
16	2.5	3.3	1.3	22.0	45.2	17.6	34.1	42.1
17	3.3	4.1	1.3	29.7	53.7	20.7	37.4	42.8
18	4.1	5.0	1.3	37.9	62.8	24.0	40.9	43.5
19	4.9	5.9	1.3	46.5	72.3	27.4	44.6	44.3
20	5.8	6.8	1.3	55.6	82.4	31.0	48.5	45.1
21	6.7	7.8	1.3	65.1	93.0	34.8	52.7	45.9
22	7.7	8.8	1.3	75.1	104.1	38.8	57.0	46.8
23	8.7	9.9	1.3	85.6	115.8	43.0	61.5	47.7
24	9.7	11.1	1.3	96.5	127.9	47.4	66.2	48.6
25	10.8	12.3	1.3	108.0	140.6	51.9	71.1	49.6
26	12.0	13.5	1.3	119.8	153.8	56.7	76.3	50.7

TABLE 12-39C.—*White oak lumber grade volume in 1-, 2-, and 3-log grade-3 trees* (Hanks 1976a)[1]—Continued

Dbh (inches)	FAS	FASIF	Sel	1C	2C	SW[2]	3A	3B
	Board feet							
			3 LOGS					
14	1.2	1.9	2.3	0.0	39.5	21.7	43.6	66.6
15	1.9	2.6	2.3	2.2	50.3	25.6	46.8	66.9
16	2.5	3.3	2.3	13.0	61.8	29.7	50.1	67.3
17	3.3	4.1	2.3	24.6	74.1	34.1	53.6	67.7
18	4.1	5.0	2.3	36.9	87.1	38.7	57.4	68.1
19	4.9	5.9	2.3	49.8	100.9	43.6	61.3	68.5
20	5.8	6.8	2.3	63.5	115.4	48.8	65.5	69.0
21	6.7	7.8	2.3	77.8	130.7	54.2	69.9	69.4
22	7.7	8.8	2.3	92.9	146.7	59.9	74.5	69.9
23	8.7	9.9	2.3	108.6	163.4	65.8	79.4	70.5
24	9.7	11.1	2.3	125.1	180.9	72.1	84.4	71.0
25	10.8	12.3	2.3	142.2	199.1	78.6	89.7	71.6
26	12.0	13.5	2.3	160.1	218.1	85.3	95.1	72.2

[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long.

[2] SW means sound wormy. See text for meaning of other abbreviations.

TABLE 12-40A.—*Yellow-poplar lumber grade volume in 2-, 3-, and 4-log, grade-1 trees* **(Hanks 1976a)**[1]

Dbh (inches)	FAS	Sel	Saps[2]	1C	2A	2B	3C
	Board feet						
		2 LOGS					
16	0.0	0.0	8.5	53.3	92.8	26.0	0.9
17	.0	1.6	10.3	74.0	102.6	23.3	1.6
18	.6	3.3	12.2	96.1	113.0	20.4	2.2
19	1.7	5.2	14.2	119.4	124.0	17.3	3.0
20	2.8	7.1	16.4	143.9	135.5	14.1	3.7
21	4.0	9.2	18.6	169.7	147.7	10.7	4.5
22	5.2	11.3	20.9	196.8	160.4	7.2	5.4
23	6.5	13.6	23.4	225.1	173.7	3.5	6.3
24	7.8	16.0	26.0	254.7	187.7	.0	7.2
25	9.2	18.4	28.6	285.5	202.2	.0	8.2
26	10.7	21.0	31.4	317.6	217.3	.0	9.2
		3 LOGS					
16	0.0	3.4	8.5	57.8	117.1	55.3	3.3
17	.4	5.2	10.3	78.3	126.5	57.9	3.6
18	1.5	7.2	12.2	100.0	136.5	60.7	3.8
19	2.7	9.2	14.2	123.0	147.1	63.6	4.1
20	4.0	11.4	16.4	147.2	158.2	66.7	4.3
21	5.3	13.7	18.6	172.7	169.9	69.9	4.6
22	6.6	16.1	20.9	199.4	182.2	73.3	4.9
23	8.1	18.6	23.4	227.4	195.0	76.9	5.2
24	9.6	21.3	26.0	256.6	208.4	80.6	5.5
25	11.1	24.0	28.6	287.0	222.4	84.4	5.9
26	12.8	26.9	31.4	318.7	237.0	88.5	6.2
27	14.5	29.8	34.3	351.7	252.1	92.6	6.6
28	16.2	32.9	37.3	385.8	267.8	97.0	7.0
29	18.0	36.1	40.4	421.2	284.0	101.5	7.3
		4 LOGS					
16	0.0	6.8	8.5	62.2	141.3	84.7	5.8
17	1.2	8.8	10.3	82.5	150.4	92.6	5.6
18	2.4	11.0	12.2	103.9	160.0	101.0	5.4
19	3.7	13.3	14.2	126.6	170.1	109.9	5.1
20	5.1	15.7	16.4	150.6	180.9	119.3	4.9
21	6.6	18.2	18.6	175.7	192.1	129.1	4.7
22	8.1	20.9	20.9	202.1	203.9	139.5	4.4
23	9.7	23.7	23.4	229.7	216.3	150.3	4.1
24	11.4	26.6	26.0	258.5	229.2	161.6	3.8
25	13.1	29.6	28.6	288.6	242.6	173.3	3.6
26	14.9	32.8	31.4	319.8	256.6	185.6	3.2

[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long.

[2] Saps means sap grade, no restriction in the amount of sapwood or heartwood. See text for meaning of other abbreviations.

TABLE 12-40B.—*Yellow-poplar lumber grade volume in 2-, 3-, and 4-log, grade-2 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	Sel	Saps[2]	1C	2A	2B	3C
				Board feet			
		2 LOGS					
13	0.0	0.0	4.0	4.4	68.5	21.5	0.2
14	.0	.5	4.8	18.8	73.5	23.2	9
15	.2	1.1	5.7	34.1	78.9	25.0	1.7
16	.4	1.7	6.7	50.6	84.6	26.9	2.5
17	.6	2.4	7.8	68.1	90.8	28.9	3.4
18	.8	3.1	8.9	86.6	97.2	31.1	4.4
19	1.0	3.8	10.0	106.3	104.1	33.4	5.3
20	1.2	4.6	11.3	126.9	111.3	35.8	6.4
21	1.5	5.4	12.6	148.7	118.9	38.4	7.5
22	1.8	6.3	13.9	171.5	126.9	41.1	8.6
23	2.0	7.2	15.4	195.3	135.3	43.9	9.8
24	2.3	8.1	16.9	220.3	144.0	46.8	11.1
25	2.6	9.1	18.4	246.2	153.1	49.8	12.4
26	2.9	10.1	20.0	273.3	162.5	53.0	13.8
		3 LOGS					
13	0.0	0.0	6.0	15.0	63.4	51.9	0.2
14	.0	.0	6.6	29.4	74.3	54.8	9
15	.2	.6	7.4	44.9	86.1	57.9	1.7
16	.4	1.6	8.1	61.5	98.7	61.2	2.5
17	.6	2.6	9.0	79.1	112.0	64.8	3.4
18	.8	3.7	9.8	97.8	126.2	68.5	4.4
19	1.0	4.8	10.8	117.5	141.2	72.5	5.3
20	1.2	6.0	11.7	138.3	157.0	76.7	6.4
21	1.5	7.3	12.8	160.2	173.6	81.1	7.5
22	1.8	8.6	13.8	183.2	191.0	85.7	8.6
23	2.0	10.0	14.9	207.2	209.3	90.6	9.8
24	2.3	11.5	16.1	232.3	228.3	95.6	11.1
25	2.6	13.0	17.3	258.5	248.2	100.9	12.4
26	2.9	14.5	18.6	285.7	268.8	106.3	13.8
		4 LOGS					
16	0.4	1.5	9.6	72.3	112.7	95.6	2.5
17	.6	2.9	10.2	90.1	133.3	100.6	3.4
18	.8	4.3	10.8	108.9	155.2	106.0	4.4
19	1.0	5.9	11.5	128.8	178.3	111.6	5.3
20	1.2	7.5	12.2	149.8	202.7	117.6	6.4
21	1.5	9.2	12.9	171.8	228.3	123.8	7.5
22	1.8	11.0	13.7	194.9	255.2	130.4	8.6
23	2.0	12.8	14.5	219.1	283.3	137.2	9.8
24	2.3	14.8	15.4	244.4	312.6	144.4	11.1
25	2.6	16.8	16.3	270.7	343.3	151.9	12.4
26	2.9	19.0	17.2	298.2	375.1	159.7	13.8

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[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long.

[2] Saps means sap grade, no restriction in the amount of sapwood or heartwood. See text for meaning of other abbreviations.

TABLE 12-40C.—*Yellow-poplar lumber grade volume in 2-, 3-, and 4-log, grade-3 trees* (Hanks 1976a)[1]

Dbh (inches)	FAS	Sel	Saps[2]	1C	2A	2B	3C
	Board feet						
		2 LOGS					
10	0.0	1.0	0.4	0.0	21.2	12.0	6.2
11	.0	.9	.6	.0	26.7	18.6	6.4
12	.0	.8	.8	1.9	32.8	25.9	6.6
13	.0	.7	1.1	11.5	39.4	33.7	6.8
14	.0	.6	1.3	21.9	46.5	42.2	7.1
15	.0	.4	1.6	33.1	54.1	51.4	7.4
16	.0	.3	1.9	45.0	62.3	61.1	7.6
17	.0	.1	2.2	57.7	70.9	71.5	7.9
18	.0	.0	2.5	71.2	80.1	82.5	8.3
		3 LOGS					
13	0.0	1.0	1.1	11.5	37.3	75.0	6.8
14	.0	1.2	1.3	21.9	49.4	82.6	7.1
15	.0	1.4	1.6	33.1	62.4	90.7	7.4
16	.0	1.6	1.9	45.0	76.3	99.4	7.6
17	.0	1.9	2.2	57.7	91.1	108.6	7.9
18	.0	2.2	2.5	71.2	106.8	118.4	8.3
19	.0	2.4	2.9	85.4	123.4	128.8	8.6
20	.0	2.7	3.2	100.4	140.9	139.7	9.0
21	.0	3.0	3.6	116.2	159.3	151.2	9.3
22	.0	3.4	4.0	132.8	178.6	163.2	9.7
23	.0	3.7	4.4	150.1	198.8	175.8	10.1
24	.0	4.1	4.9	168.2	219.9	189.0	10.6
		4 LOGS					
15	0.0	2.4	1.6	33.1	70.7	130.1	7.4
16	.0	3.0	1.9	45.0	90.4	137.7	7.6
17	.0	3.7	2.2	57.7	111.3	145.8	7.9
18	.0	4.4	2.5	71.2	133.5	154.3	8.3
19	.0	5.1	2.9	85.4	157.0	163.4	8.6
20	.0	5.9	3.2	100.4	181.7	173.0	9.0
21	.0	6.8	3.6	116.2	207.8	183.0	9.3
22	.0	7.6	4.0	132.8	235.0	193.6	9.7
23	.0	8.6	4.4	150.1	263.6	204.6	10.1
24	.0	9.5	4.9	168.2	293.4	216.1	10.6

[1] Based on U.S. Forest Service tree grades; lumber graded when green according to rules of the National Hardwood Lumber Association (1974). A 2-log tree contains two logs each nominally 16 feet long.

[2] Saps means sap grade, no restriction in the amount of sapwood or heartwood. See text for meaning of other abbreviations.

Grading hardwood sawtimber trees.—Sawtimber trees are graded on a similar basis to sawlogs. The log grade of the best three faces of the grading section determines the grade of the tree. The following procedure is used (Hanks 1976a):

1. Measure tree dbh to the nearest inch.
2. Establish the location of all defects on the surface of the butt 16-foot log and then locate the best 12-foot section of the butt log.
3. Estimate the inside bark diameter at the top of the 12-foot section to the nearest inch.
4. Estimate the scalable defect in the 12-foot section selected previously.
5. The grade of the 12-foot section becomes the tree grade unless the grade can be improved by using a 14- or 16-foot section. The highest grade of the 12-, 14-, or 16-foot section determines the tree grade.

Many hardwood trees are classified low grade due to size. The smallest diameter tree that can qualify for grade 1 is 16 inches dbh; to be considered for grade 2 a tree must be at least 13 inches dbh; and a tree must be at least 10 inches to qualify for grade 3 (table 12-34). A rapid increase in butt log grade with increasing tree diameter was shown for northern red oak in West Virginia (Trimble 1965). Based on an evaluation of the butt log grades of 578 northern red oak trees, Trimble reported that only 20 percent of the 12-inch dbh trees were of grade 3 or better quality, whereas 15 percent of the 14-inch trees graded 2 or better, and 55 percent of the 20-inch trees were grade 1. Similar increases in tree grade with diameter increases were also noted for yellow-poplar and chestnut oak. White oak and sugar maple showed a consistent grade increase with diameter, but at a slower rate than northern red oak, yellow-poplar, and chestnut oak. Beech showed the least improvement in butt log grade with increasing tree size.

Lumber grade yield for trees.—Tables 12-35 through 12-40 show lumber grade yield from tree grades 1, 2, and 3 of red maple, yellow-poplar, and black, northern red, white, and chestnut oaks containing from one to four 16-foot logs.

The lumber grade yields in the tables are based on sawing studies at several mills at different locations. Lumber grade yields from these tables may vary from that of a particular mill which may be using different equipment or sawing different lumber products or thicknesses. If a mill operator wants to develop lumber grade yield predictions for graded trees that are typical of his operation, a procedure has been developed (Hanks 1976b). It is recommended that this same procedure be used to develop tree grade-lumber yield information for species for which tree grade information has not yet been developed.

Tree grades of growing stock.—A method of grading small diameter hardwood trees to predict future tree grade has been proposed (Boyce and Carpenter 1968). The specifications are for growing stock trees from 7 to 15 inches in dbh (table 12-41). The tree grades are assigned based on the probability of a tree yielding a grade 1, grade 2, or a grade 3 butt log when it reaches 16 inches dbh. The grades are defined as follows:

1. A grade 1 growing stock tree has an 80 percent probability or better of yielding a grade 1 butt log 12, 14, or 16 feet long.
2. A grade 2 growing stock tree has less than an 80 percent probability of yielding a grade 1 butt log, but a 50 percent chance or better of yielding a grade 2 butt log.
3. A grade 3 growing stock tree has less than a 50 percent probability of yielding a grade 2 butt log, but a 50 percent chance or better of yielding a grade 3 butt log.

These specifications can be applied during thinning operations to decide which trees to remove and which ones to favor.

TABLE 12-41.—*Provisional grade specifications for hardwood growing stock trees* (Boyce and Carpenter 1968)

Growing-stock grades	Grading factors						
	Dbh	Crown class	Length of butt log	Scaling deductions	Sweep, maximum	Lean, maximum	Surface defect indicators
	Inches		*Feet*		*Inches*	*Degrees*	*Number*
1	7-15	Dominants and codominants	12, 14, 16	Only sweep admitted	4	4	2
2	7-15	Dominants and codominants	12, 14, 16	Only sweep admitted	6	6	3-13
3	7-15	Dominants and codominants	12, 14, 16	Only sweep admitted	8	8	14-19

Sonderman and Brisbin (1978) have suggested another quality classification system for small hardwood trees based on measurement of crown class, degree of sweep and crook, and limb count (table 12-42). By their system, index numbers obtained by summing values from table 12-42 indicate quality classes as follows:

Index number	Quality class of tree
10–12	Good
8–9	Medium
1–7	Poor

TABLE 12-42.—*Values assigned to three tree characteristics to determine quality of young hardwood trees* (Sonderman and Brisbin 1978)

Characteristic and description	Value
Crown class	
Dominant	4
Codominant	3
Intermediate	2
Suppressed	1
Sweep and crook, inches deviation[1]	
1	4
2–4	3
5–6	2
7–8	1
9+	0
Limb count[2]	
1–2	4
3–4	3
5–8	2
9–16	1
17+	0

[1] Measured in butt 16-foot portion of stem; if tree has forks, rot, or seams in this stem portion then value under this characteristic = 0.

[2] Number of live and dead limbs 1/3-inch and larger in diameter on butt 16-foot portion of stem.

12-9 LITERATURE CITED

American Plywood Association. 1974b. U.S. Product Standard PS 1-74 for construction and industrial plywood with typical APA trademarks. Amer. Plyw. Assoc., Tacoma, Wash. 35 p.

American Plywood Association. 1974a. Plywood product standard handbook. U.S. Prod. Stand. PS 1-74 for Constr. and Ind. Plywood. 100 p. Tacoma, Wa.: Am. Plywood Assoc.

American Railway Engineering Association. 1970. AREA manual for railway engineering. Chap. 3—Ties. Amer. Railway Eng. Assoc., Chicago, Ill. 42 p.

Bingham, S. A., and J. G. Schroeder. 1976. Short lumber in manufacture. Part II. Bolt and lumber grading. Natl. Hardw. Mag. 50(12):90, 91, 112.

Boyce, S. G., and R. D. Carpenter. 1968. Provisional grade specifications for hardwood growing-stock trees. Res. Pap. NE-97. U.S. Dep. Agric., For. Serv. 12 p.

Butin, H., and A. L. Shigo. 1981. Radial shakes and "frost cracks" in living oak trees. U.S. Dep. Agric., For. Serv., Res. Pap. NE-478. 21 p.

Calvert, W. W. 1955. Increasing hardwood lumber yields with the short-log bolter. Timber of Can. 15(6):25-43.

Campbell, R. A. 1951. Tree grades, yields and values for some Appalachian hardwoods. U.S. Dep. Agric. For. Serv., Stn. Pap. No. 9. 26 p. Southeast. For. Exp. Stn., Asheville, N.C.

Campbell, R. A. 1959. Tree grades give accurate estimate of second-growth yellow-poplar values. U.S. Dep. Agric. For. Serv., Stn. Pap. No. 108. 14 p. Southeast. For. Exp. Stn., Asheville, N.C.

Church, T. W., Jr. 1973. The significance of sweep in Appalachian hardwood sawlogs. U.S. Dep. Agric. For. Serv., Res. Note NE-172. 4 p.

Craft, E. P. 1970. Construction-grade plywood from grade 3 Appalachian oak. U.S. Dep. Agric. For. Serv., Res. Pap. NE-163. 30 p.

Craft, E. P. 1971. Construction grade plywood from grade 3 hardwoods—an industrial possibility. For. Prod. J. 21(2):26-30.

Dunmire, D. E., R. L. Brisbin, R. Gale, and J. K. Sherwood. 1974. Furniture square yields from graded maple bolts. *In* Whole tree utilization of hardwoods. Proc. of Sec. Ann. Hardwood Symp. of the Hardwood Research Council. May 2-4, Cashiers, N.C. p. 129-141.

Dunmire, D. E., E. F. Landt, and R. E. Bodkin. 1972. Logging residue is a source of valuable black walnut dimension. For. Prod. J. 22(1):13-17.

Hanks, L. F. 1971. Interim hardwood tree grades for factory lumber. Res. Pap. NE-199, U.S. Dep. Agric., For. Serv. 29 p.

Hanks, L. F. 1973. Green lumber grade yields for subfactory class hardwood logs. U.S. Dep. Agric. For. Serv., Res. Pap. NE-256. 7 p.

Hanks, L. F. 1976a. Hardwood tree grades for factory lumber. U.S. Dep. Agric. For. Serv., Res. Pap. NE-333. 81 p.

Hanks, L. F. 1976b. How to predict lumber-grade yields for graded trees. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. NE-20. 9 p.

Hanks, L. F., G. L. Gammon, R. L. Brisbin, and E. D. Rast. 1980. Hardwood log grades and lumber grade yields for factory lumber logs. U.S. Dep. Agric., For. Serv., Res. Pap. NE-468. 92 p.

Harrar, E. S. and R. A. Campbell. 1966. The major defects in southern hardwood veneer logs and bolts. U.S. Dep. Agric. For. Serv., Res. Pap. SE-19. 23 p.

Henley, J. W., R. O. Woodfin, Jr., and H. H. Haskell. 1963. Recommended veneer grades for the development of hardwood veneer log grades. U.S. Dep. Agric. For. Serv. Res. Pap. FPL 9. 12 p.

Herrick, A. M. 1958. Grading and measuring hickory trees, logs, and products. U.S. Dep. Agric. For. Serv., Hickory Task Force Rep. No. 7. 18 p. Southeast. For. Exp. Stn., Asheville, N.C.

Herrick, D. E. and W. L. Jackson. 1957. The butt log tells the story. U.S. Dep. Agric. For. Serv., Note No. 102. 2 p. Cent. States For. Exp. Stn., Columbus, Ohio.

Huffman, J. B. 1973. Comparative yields of furniture parts cut from short bolts and conventional logs of Florida red maple. 25 p. Fla. Dep. Agric., Div. For. Tallahassee.

Hyvarinen, M. J. 1968. Using d.b.h. and butt log quality to estimate tree yields by saw log grade. U.S. Dep. Agric., For. Serv., Res. Note NC-67. 2 p.

Kroon, M. J. 1974. Sawing furniture quality dimension from short log bolts. M.S. Thesis. Mich. State Univ., East Lansing. 67 p.

Landt, E. F. 1974a. Aspen volume tables for furniture-type, flat, 4/4-inch dimension. Res. Note NC-166, U.S. Dep. Agric., For. Serv. 2 p.

Landt, E. F. 1974b. Black cherry volume tables for furniture-type, flat 4/4-inch dimension from small low-quality trees. Res. Note NC-167, U.S. Dep. Agric., For. Serv. 2 p.

Landt, E. F. 1974c. Black walnut volume tables for furniture-type, flat, 4/4-inch dimension for small low-quality trees. Res. Note NC-168, U.S. Dep. Agric., For. Serv. 2 p.

Landt, E. F. 1974d. Soft maple volume tables for furniture-type, flat, 4/4-inch dimension from small low-quality trees. U.S. Dep. Agric. For. Serv., Res. Note NC-169. 2 p.

Lockard, C. R., J. A. Putnam, and R. D. Carpenter. 1963. Grade defects in hardwood timber and logs. U.S. Dep. Agric. For. Serv., Agric. Handb. 244. 39 p. U.S. Govt. Print. Off., Washington, D.C.

Lucas, E. L. 1969. An approach to yellow-poplar tree valuation. U.S. Dep. Agric. For. Serv., Res. Pap. NE-137.

Lutz, J. F. 1975. Manufacture of veneer and plywood from United States hardwoods with special reference to the South. U.S. Dep. Agric. For. Serv. Res. Pap. FPL 255. 9 p.

Marden, R. M. 1965. A new approach to tree grading for northern hardwoods. For. Prod. J. 15:179-184.

McAlister, R. H. 1981. Evaluation of veneer yields and grades from yellow-poplar, white oak, and sweetgum from the Southeast. Res. Pap. SE-220, U.S. Dep. Agric., For. Serv. COM-PLY Rep. 19, Southeast. For. Exp. Stn., Asheville, N.C.

McAlister, R. H., and A. Clark III. In press. Veneer yields by grade from three Coastal Plain hardwoods—blackgum, sweetgum, and yellow-poplar. Southeast. For. Exp. Stn., U.S. Dep. Agric., For. Serv., Asheville, N.C.

Murphy, P. A. and H. A. Knight. 1974. Hardwood resources on southern pine sites. For. Prod. J. 24(7):13-16.

National Bureau of Standards. 1972. Hardwood and decorative plywood. Voluntary Prod. Stand. PS-51-71. U.S. Dep. Commerce, Washington, D.C.

Northern Hardwood and Pine Manufacturers Assn., Inc. 1978. Standard grading rules. Northern Hardwood and Pine Manufacturers Assn., Inc., Green Bay, Wis.

National Hardwood Lumber Association. 1974. Rules for the measurement & inspection of hardwood & cypress lumber and the national hardwood lumber sales code. 117 p. Chicago, Ill.: Nat. Hardwood Lumber Assoc.

National Hardwood Lumber Assocation. 1978. Rules for the measurement and inspection of hardwood and cypress lumber. 115 p. Chicago, Ill.: Nat. Hardwood Lumber Assoc.

Petro, F. J. 1975. Felling and bucking hardwoods—how to improve your profit. Can. For. Serv. Publ. No. 1291. 141 p. Ottawa, Can.

Putnam, J. A., G. M. Furnival, and J. S. McKnight. 1960. Management and inventory of southern hardwoods. U.S. Dep. Agric., For. Serv., Agric. Handb. 181. 102 p.

Rast, E. D. 1971. Preliminary work in developing sawbolt grading systems for white oak. U.S. Dep. Agric. For. Serv., Res. Pap. NE-193. 14 p.

Rast, E. D. 1975. Preliminary hardwood log veneer grades for yellow birch and sugar maple face veneer. *In* Proc. Third Ann. Hardw. Symp., Hardw. Res. Counc., p. 84-94. (Asheville, N.C. May 1975.)

Rast, E. D., D. L. Sonderman, and G. L. Gammon. 1973. A guide to hardwood log grading. (Revised) U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. NE-1. 32 p.

Reynolds, H. W. 1974. Optimum sawing patterns for low-grade hardwoods. *In* Use of computers in forestry, 23rd annu. for. symp., pp. 119-134. Baton Rouge, La.: La. State Univ.

Reynolds, J. W., and J. Schroeder. 1977. System 6—A way to use small logs to make grade lumber for furniture cuttings. South. Lumberman 234(2897):9-10.

Schroeder, J. G. 1964. Tree grading and valuation system for yellow-poplar. For. Prod. J. 14:521-524.

Schroeder, J. G. 1968. Lumber grade yields for sub-factory class red oak logs. U.S. Dep. Agric. For. Serv., Res. Pap. NE-114. 15 p.

Schroeder, J. G. 1981. Defects and grades of hardwood logs and trees. *In* Utilization of low-grade southern hardwoods—feasibility studies of 36 enterprises. (D. A. Stumbo, ed.) p. 14-24. Forest Products Research Society, Madison, Wis.

Schroeder, J. G. and L. F. Hanks. 1967. Lumber grade-yields for factory-grade northern red oak sawlogs. U.S. Dep. Agric. For. Serv., Res. Note NE-65. 7 p.

Sonderman, D. L., and R. L. Brisbin. 1978. A quality classification system for young hardwood trees—the first step in predicting future products. U.S. Dep. Agric. For. Serv., Res. Pap. NE-419. 7 p.

Trimble, G. R., Jr. 1965. Improvement in butt-log grade with increase in tree size, for six hardwood species. U.S. Dep. Agric. For. Serv., Res. Pap. NE-31. 15 p.

U.S. Department of Commerce. 1972. Hardwood and decorative plywood. NBS Voluntary Prod. Stand. PS 51-71, 15 p. Natl. Bur. of Stand., Washington, D.C.

Yao, J. 1979. Relationships between height and growth stresses within and among white ash, water oak, and shagbark hickory. Wood Sci. 11:246-251.

Vaughan, C. L., A. C. Wollin, K. A. McDonald, and E. H. Bulgrin. 1966. Hardwood log grades for standard lumber. U.S. Dep. Agric. For. Serv., Res. Pap. FPL 63. 52 p.

PART III—BARK, ROOTS, AND FOLIAGE

Chapter	*Title*
13	BARK
14	ROOTS
15	FOLIAGE AND SEEDS

13

Bark

Section 13-1 (ANATOMY) is condensed principally from research by H. Nanko, W. A. Côté, Jr., and E. T. Howard, as described in text footnote 1. Other sources of data for section 13-1 are cited in text and tables.

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CHAPTER 13

Bark

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13-9 LITERATURE CITED 1250

CHAPTER 13

Bark

Bark comprises all the tissues outside a tree's vascular cambium. It is a significant portion of the total above-ground biomass of hardwoods found where southern pines grow. In 6-inch dbh trees of the species under study, this proportion is least in yellow-poplar (6.5 percent), and most in blackjack oak (23.1 percent)—see section 13-3. In most mills bark is removed—by methods described in chapter 17—before wood is processed into lumber, plywood, flakeboard, or pulp, and is therefore usually available in coarse particulate form. Ease of removal varies greatly with species and season, as discussed in section 17-1.

In a hundred railcars of hardwood cordwood entering a pulpmill, there are 10 to 20 carloads of bark and only 80 to 90 of wood. This bark, readily available in large quantities but little utilized except as low-value fuel or agricultural mulch, is worthy of characterization as a potential industrial raw material.

The barks vary significantly among species in external texture (figs. 3-33 through 3-58) and in color (figs. 13-1 through 13-6). Barks of most trees become thicker and coarser with age. The appearance of bark of certain species is a good indicator of tree vigor and growth rate (figs. 12-42 through 12-44). Barks of the hardwoods under study also vary among species in anatomy, thickness, moisture content, chemical composition, and physical and mechanical properties.

13-1 ANATOMY[1]

Text in this section cites prior relevant work where appropriate, but studies on structural characterization or comparative anatomy of hardwood barks are few (Holdheide 1951; Chang 1954; Zahur 1959; Parameswaran and Liese 1970; Nanko and Côté 1980); only a few workers (Martin and Crist 1970; Baldwin et al. 1974) have employed scanning electron microscopy in the study of bark tissues. Discussion in this section is mostly confined to structure. Readers needing information on tissue differentiation in bark should consult Esau's (1969) review of development of sieve elements, Cheadle and Esau's (1964) work on yellow-poplar, Artschwager's (1950) study of *Carya illinoensis* (Wangenh.) K. Koch, the work of Evert et al. (1969) on the ontogeny and structure of American elm bark, Anderson and Evert's (1965) report on phloem development in white oak, and Borger and Kozlowski's (1972) findings on the effects of temperature on periderm development in green ash.

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[1] Text and figures under this heading are adapted primarily from Nanko and Côté (1980), with additional data from Howard (1977), by permission of the authors, Syracuse University Press, and the Society of Wood Science and Technology. Nanko and Côté were concerned primarily with southern non-oak species, but did describe two oaks (white and southern red). Howard studied bark from 11 oaks (black, blackjack, cherrybark, laurel, northern red, post, scarlet, Shumard, southern red, water, and white oaks). Both studies were based on the bark of 10 trees of each species measuring about 6 inches in dbh and sampled among southern pines across the southern ranges of the hardwood species. See tables 3-1 and 16-3 for a description of the trees.

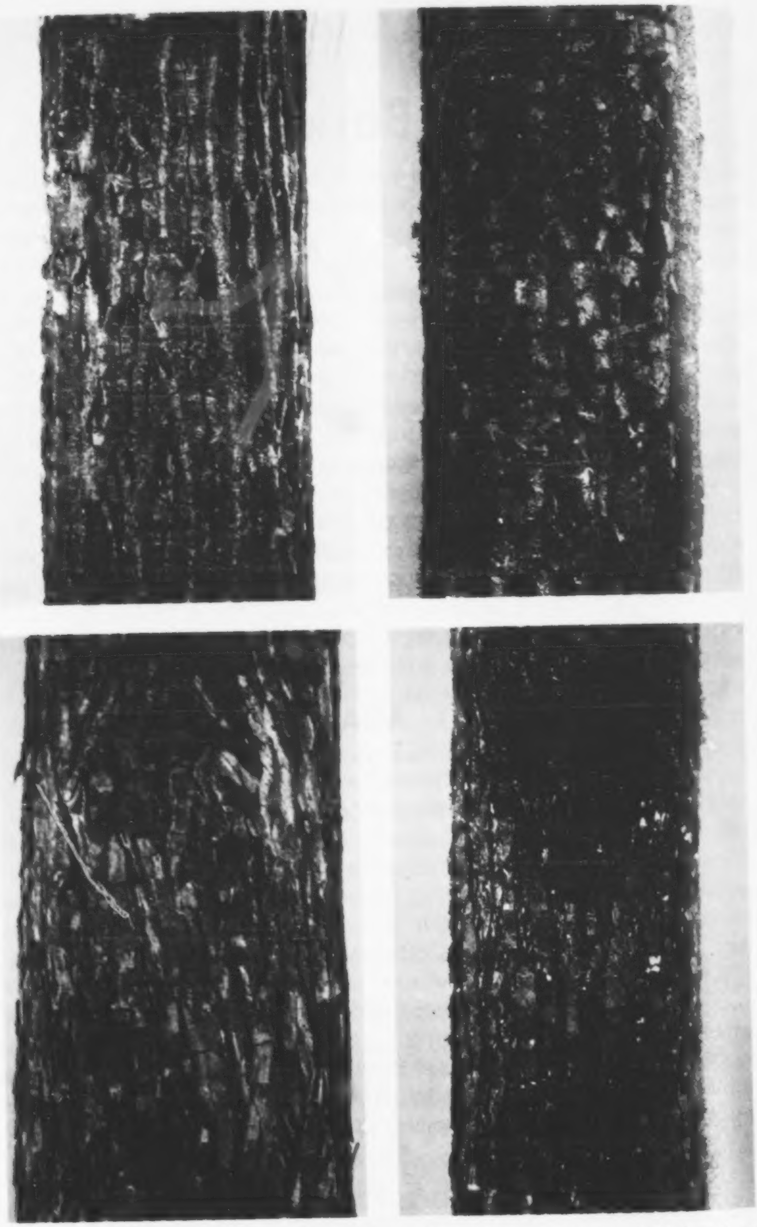


Figure 13-1.—Bark (Top left) Green ash. (Top right) White ash. (Bottom left) American elm. (Bottom right) Winged elm. Magnification X 0.3. (Photos from McMillin and Manwiller 1980.)

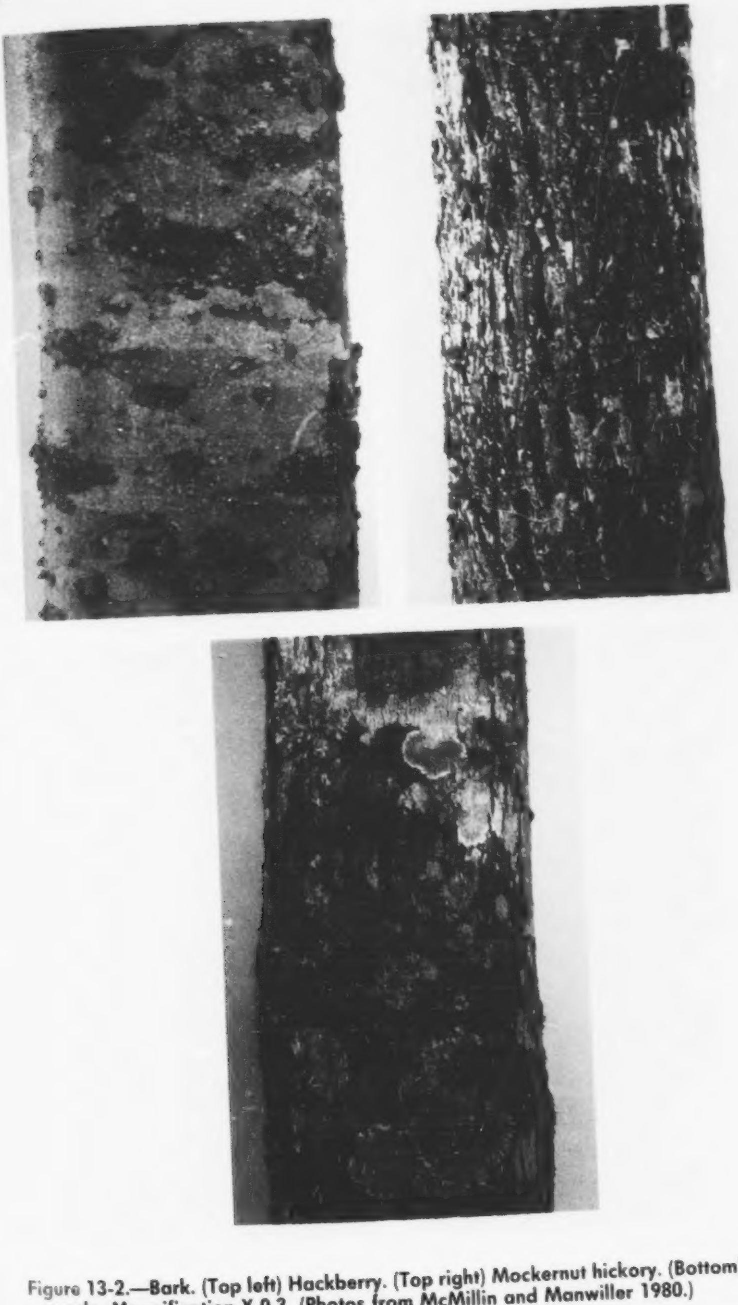


Figure 13-2.—Bark. (Top left) Hackberry. (Top right) Mockernut hickory. (Bottom) Red maple. Magnification X 0.3. (Photos from McMillin and Manwiller 1980.)

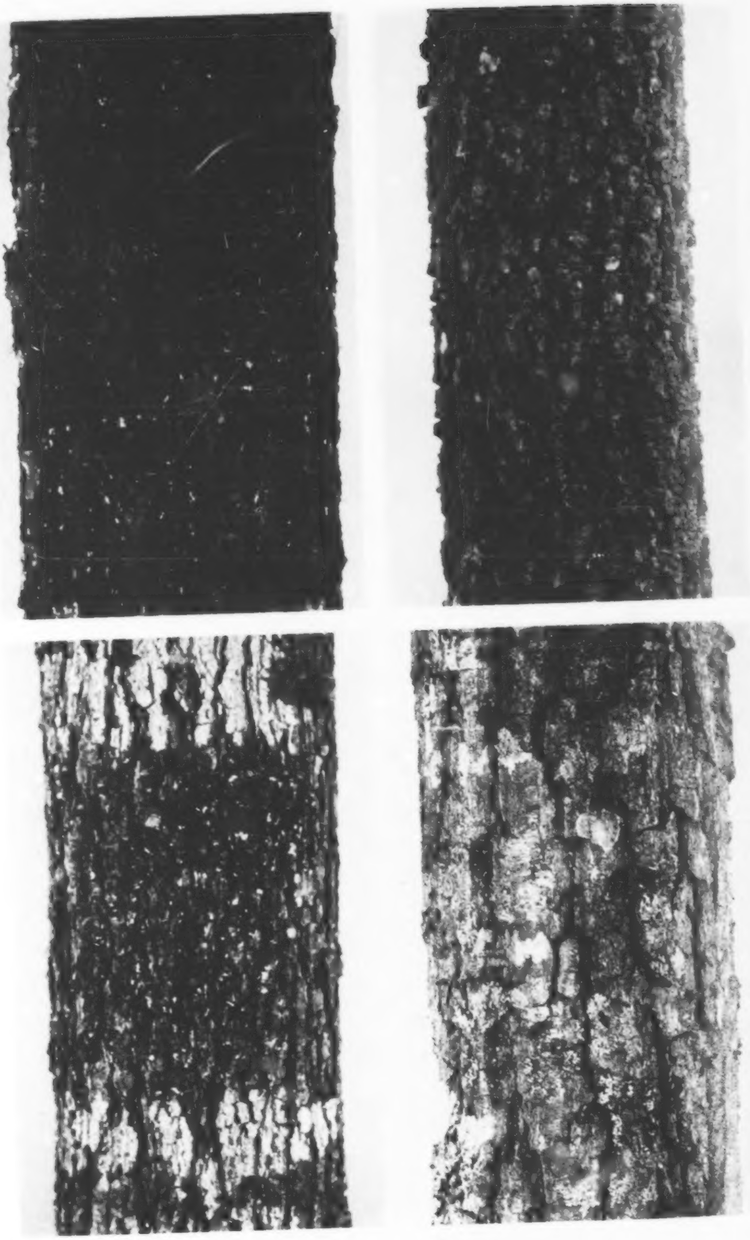


Figure 13-3.—Bark. (Top left) Black oak. (Top right) Blackjack oak. (Bottom left) Cherry bark oak. (Bottom right) Chestnut oak. Magnification X 0.3. (Photos from McMilli and Manwiller 1980.)

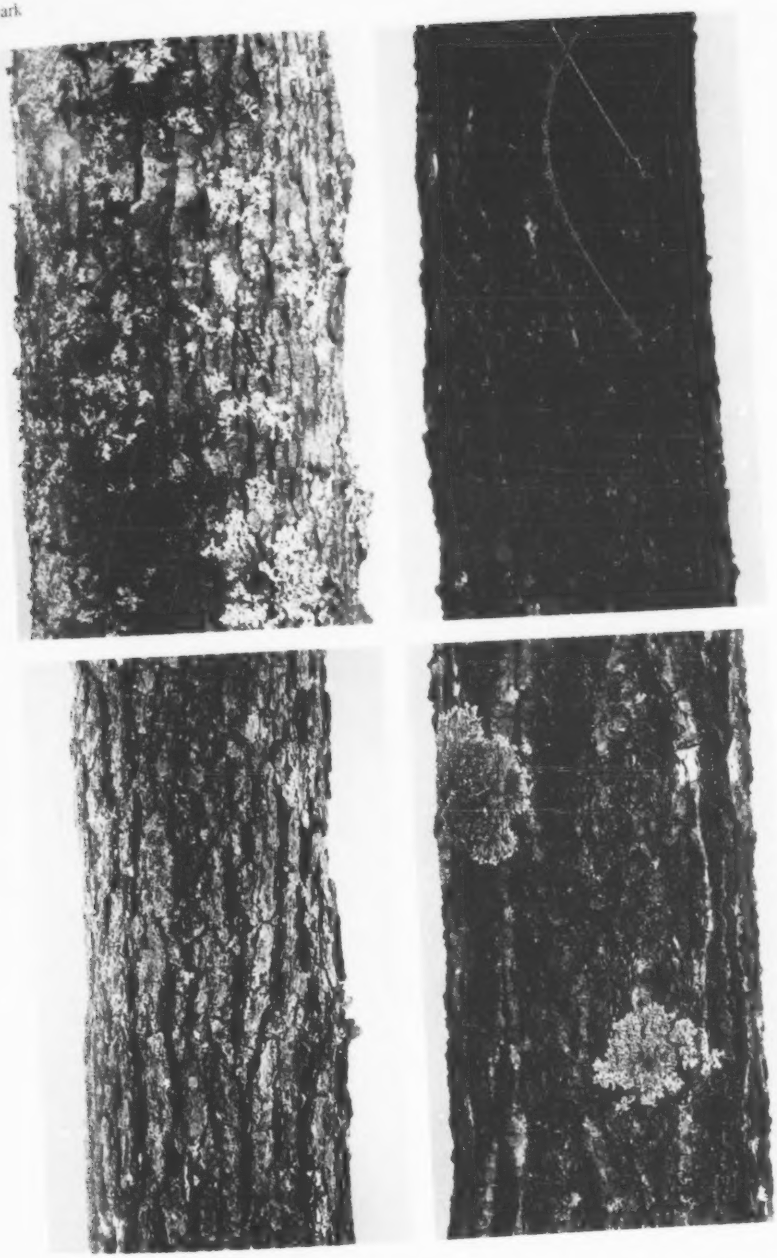


Figure 13-4.—Bark. (Top left) Laurel oak. (Top right) Northern red oak. (Bottom left) Post oak. (Bottom right) Scarlet oak. Magnification X 0.3. (Photos from McMillin and Manwiller 1980.)

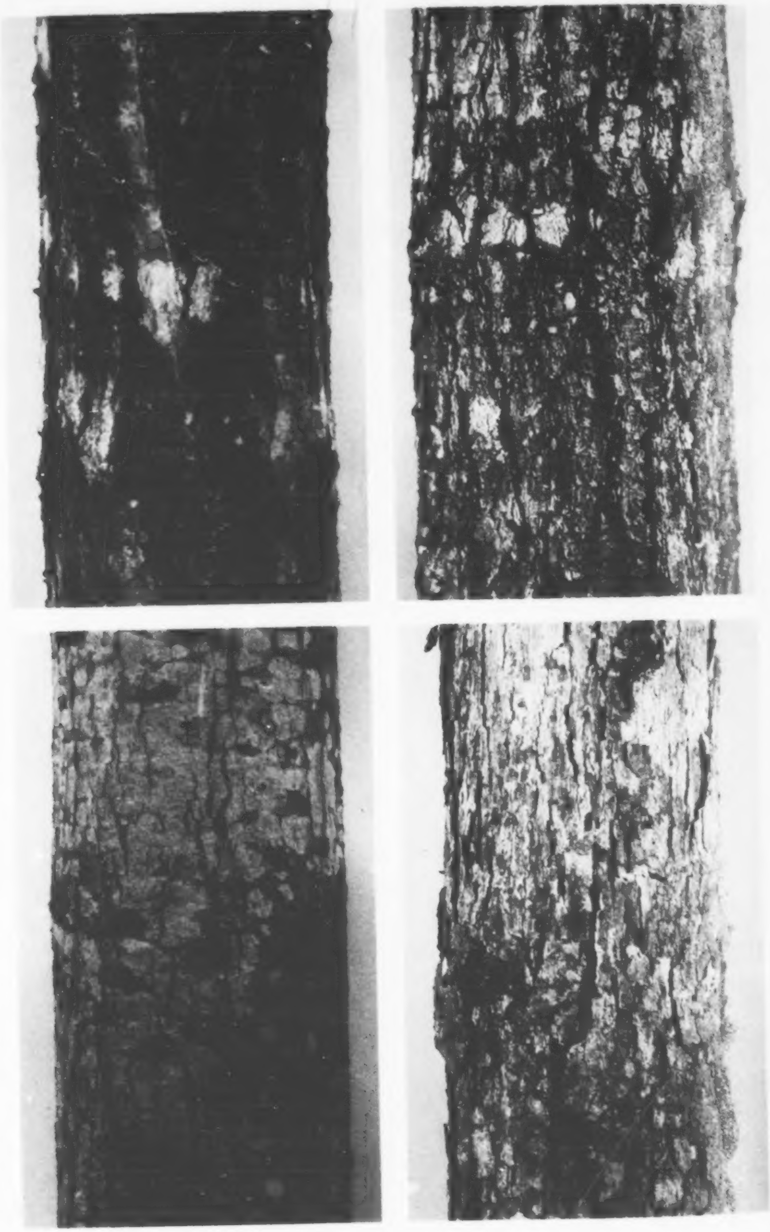


Figure 13-5.—Bark. (Top left) Shumard oak. (Top right) Southern red oak. (Bottom left) Water oak. (Bottom right) White oak. Magnification X 0.3. (Photos from McMillin and Manwiller 1980.)

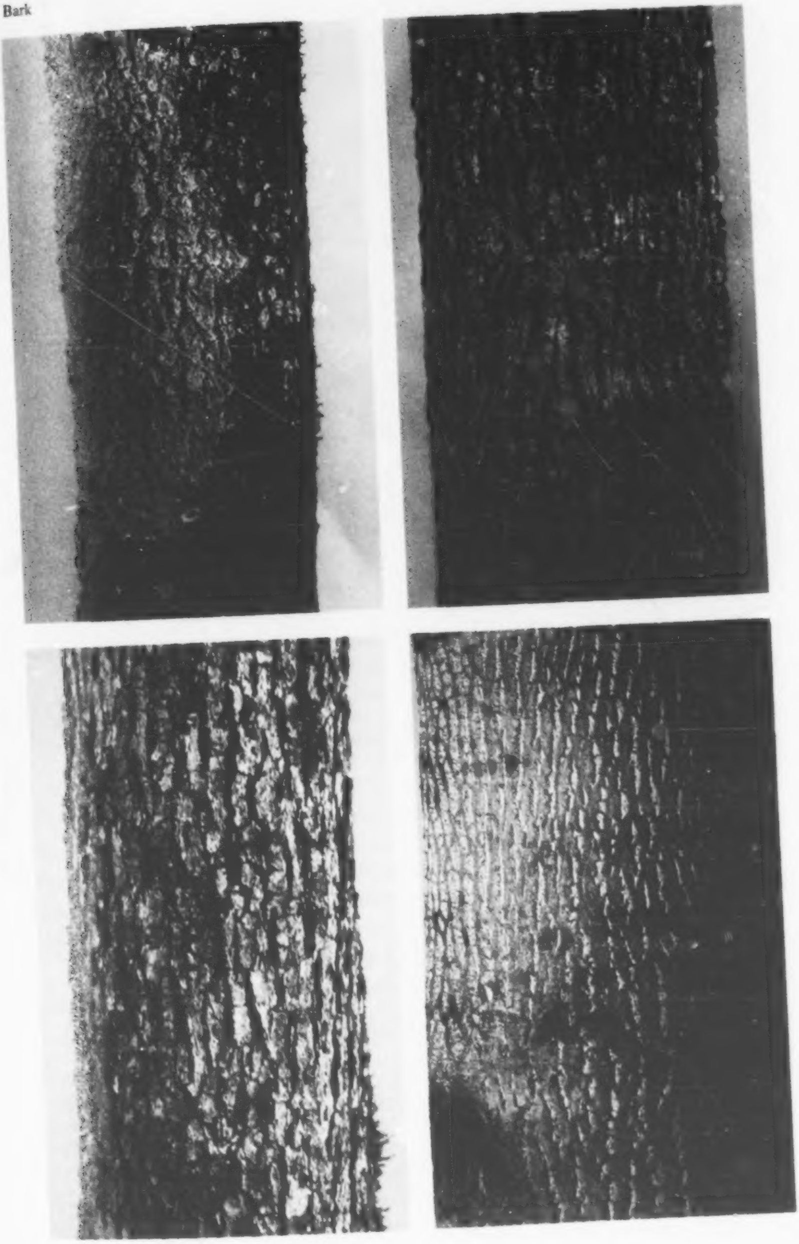


Figure 13-6.—Bark. (Top left) Sweetbay. (Top right) Sweetgum. (Bottom left) Black tupelo. (Bottom right) Yellow-poplar. Magnification X 0.3. (Photos from McMillin and Manwiller 1980.)

TERMINOLOGY

Terminology is not as firmly established for bark tissues as for wood tissues. The terminology used in this chapter is mainly taken from Esau (1965, 1969, 1977). Howard (1977) described the formation of bark and its elements in 11 pine-site oaks as follows.

The vascular cambium surrounds the tree stem at the boundary between the wood and bark. It produces wood (**xylem**) to the interior and **phloem** (conducting and storage cells of the bark) to the exterior. The layer of phloem produced each year is only a fraction as thick as the annual layer of wood. Each new layer of phloem pushes the older phloem layers outward from the enlarging wood stem.

A new tissue—the **phellogen** or **cork cambium**—appears within various areas of the older phloem at some distance outside the vascular cambium. The phellogen is a layer of dividing cells that produce tangentially oriented layers of **periderm.** The impervious periderms protect the delicate phloem tissue from harmful external influences. Portions of older phloem are sealed off from supplies of nutrients and moisture by the periderm layers, and cells of these isolated areas of phloem subsequently die. Each periderm dies when a newer one is formed further inward. The tissues are pushed outward by each year's growth; when outer layers do not flake off as rapidly as interior ones are formed, a thick, rough bark eventually accumulates. Longitudinal cracks form to accommodate tangential stresses caused by growth in the tree's girth.

BARK STRUCTURE

Bark is comprised of two portions: the light-colored **inner bark**—comprised of living secondary phloem tissues between the vascular cambium and the most recently formed periderm, and surrounding dead dark **outer bark** or **rhytidome** of dead tissues. The innermost periderm separates the two zones (figs. 13-7 and 13-8). Typical tissues and cells in barks of pine-site hardwoods are illustrated in figures 13-9 through 13-11, and listed as follows:

- Inner bark (secondary phloem)
  - Sieve tube elements
  - Fibers
  - Sclereids
  - Vertical parenchyma
  - Ray parenchyma
  - Companion cells

- Outer bark (rhytodome): see figure 13-11
  - Old phloem
  - Periderm
    - Phellogen
    - Phellem (cork)
    - Phelloderm

best copy available

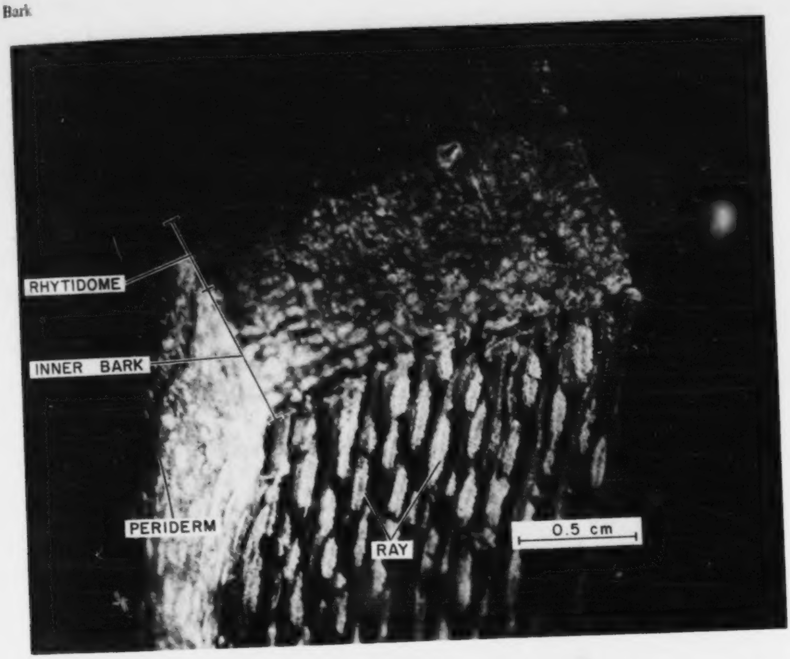

RHYTIDOME
INNER BARK
PERIDERM
RAY
0.5 cm

Figure 13-7.—Southern red oak bark, cross-sectional (top), radial (left), and tangential (foreground) views. Sclereid groups appear as white areas on cut surfaces. Rays protrude on surfaces next to cambium. (Photo from Howard 1977.)

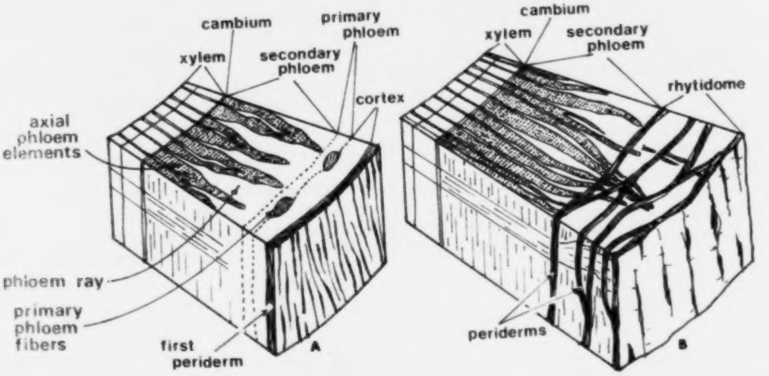

cambium
primary phloem
xylem
secondary phloem
cortex
axial phloem elements
phloem ray
primary phloem fibers
first periderm
A
cambium
xylem
secondary phloem
rhytidome
periderms
B

Figure 13-8.—Diagrams showing the difference in bark structure between a young stem (A) and an older stem (B) of yellow-poplar. The *primary phloem* is the first-formed phloem tissue; it is cut off by periderm formation and cannot be found in mature bark. Also found in bark of young stems, but not in bark of mature trees is the *cortex*, or primary ground tissue between vascular tissue and epidermis or periderm. (Drawing after Nanko and Côté 1980.)

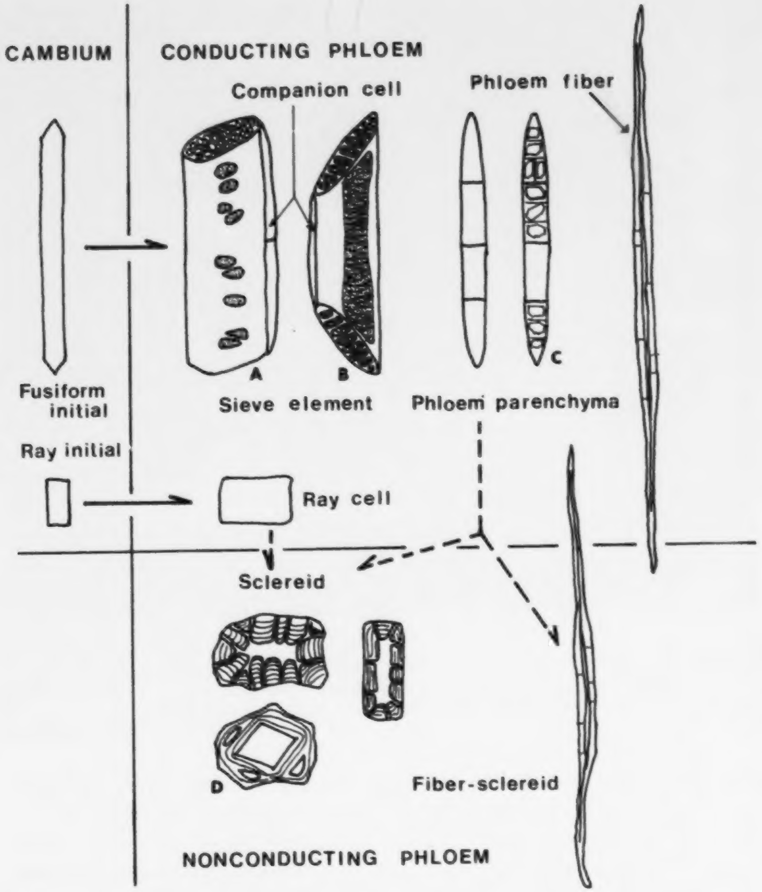

CAMBIUM
CONDUCTING PHLOEM
Companion cell
Phloem fiber
Fusiform initial
A
B
C
Sieve element
Phloem parenchyma
Ray initial
Ray cell
Sclereid
D
Fiber-sclereid
NONCONDUCTING PHLOEM

Figure 13-9.—Diagram showing cell types in secondary phloem of hardwood barks and their ontogenetic development. (A) Sieve element with simple sieve plate; (B) sieve element with compound sieve plate; (C) crystal-containing sclerified cell; (D) sclereid. (Drawing after Nanko and Côté 1980.)

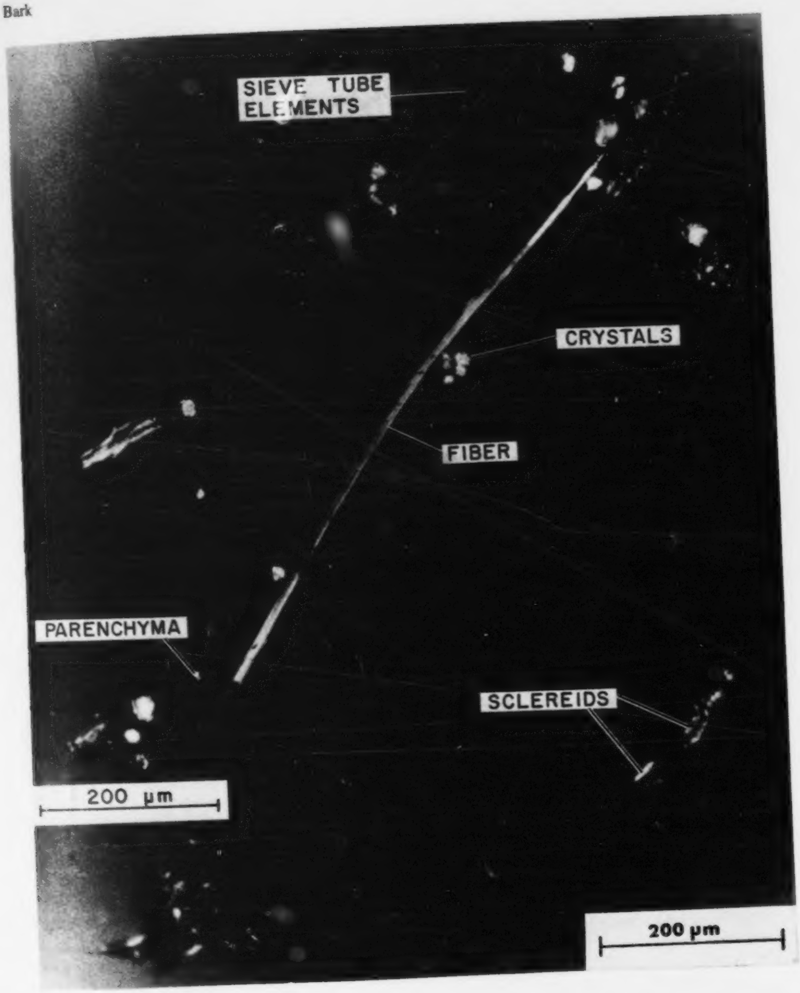

SIEVE TUBE ELEMENTS
CRYSTALS
FIBER
PARENCHYMA
SCLEREIDS
200 µm
200 µm

Figure 13-10.—Macerated bark from southern red oak. Fibers are the only greatly elongated elements in bark. (Photo from Howard 1977.)

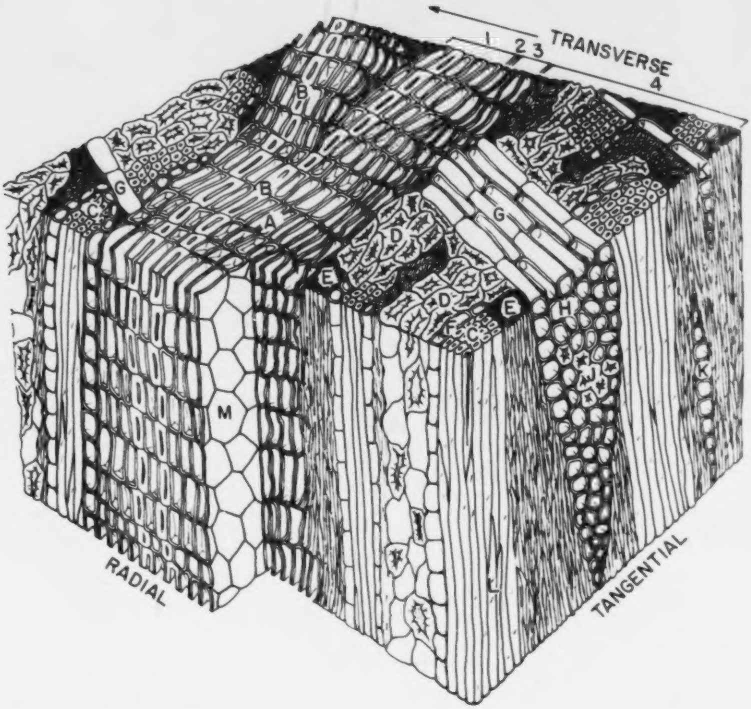


Figure 13-11.—Schematic drawing of periderm and adjacent tissues in outer bark from southern upland oaks. Periderm is comprised of 1, 2, and 3. Arrow points toward tree exterior. *Transverse view.* 1. Phellem: A, typical cork cells; B, thick-walled cork band. 2. Phellogen (cork cambium). 3. Phelloderm. 4. Old phloem tissue: C, fibers; D, sclereids; E, collapsed thin-walled elements (sieve tubes, companion cells, parenchyma); F, crystal-bearing parenchyma along margins of fiber groups; G, ray parenchyma. *Tangential view.* H, broad ray; J, sclerified ray cells; K, narrow ray; L, fiber group; M, polygonal phellem arrangement. (Drawing after Howard 1977.)

Figures that follow in this section are labelled according to the following key (for general descriptions of individual species see figures 13-31 through 13-57):

Key to symbols used on figures

c	cambium	pe	periderm
co	companion cell	pg	phellogen
cp	conducting phloem	ph	phellem
cr	crystal	r	rhytidome
cs	crystalliferous sclerified cell	ra	ray
f	fiber (phloem fiber, fiber-sclereid)	s	sieve elements
G	gelatinous layer	S1	S1 layer
n	nacreous thickening	S2	S2 layer
np	nonconducting phloem	sa	sieve area
p	secondary phloem	sc	sclereid
pa	phloem parenchyma	sp	sieve plate
pd	phelloderm	x	xylem

Periderms.—The innermost periderm is a living tissue which protects the inner bark from moisture loss and from pathogens. Periderms are usually readily visible on transverse sections as discontinuous lines of variable pattern more or less concentric to tree circumference. A periderm is composed of three tissues—phellogen, phellem, and phelloderm. The **phellogen,** or **cork cambium,** is a cell layer that forms cork (**phellem**) toward the outside and parenchyma (**phelloderm**) on the inside (Esau 1977). Early phellogens arise from cortical cells, but in older bark they arise from parenchyma of the nonfunctional phloem. The derivative cells retain the polygonal shape of the mother phellogen cell for the most part but differ in wall structure. They are in distinct radial alignment but are not aligned tangentially (fig. 13-11). Periderm width depends on length of life of its phellogen; if it is replaced by a new phellogen deeper in the bark after a brief period of activity, only a few layers of cells are produced and the periderm is narrow. The phellem, or cork tissue, is the primary barrier preventing moisture loss from the stem. The frequency and the manner of periderm formation differ by species and contribute characteristic bark features. In some trees, such as sweetbay, the first periderm is quite persistent but in others, such as the oaks, periderm formation may recur frequently.

Periderms in oak sp.—Howard (1977) noted that oaks of the species studied do not produce extensive cork layers as does cork oak (*Quercus suber* L.). Phellem is a compact tissue of small cells that appear as flat rectangles in radial and cross sections, and are polygonal in tangential view (fig. 13-11). Typical hardwood cork cells have unpitted cellulose walls with a secondary wall of suberin, composed of alternating phenolic and wax lamellae, that renders them practically impervious to moisture and gases (Sitte 1957; Esau 1965). In the oaks studied, typical cork cells comprise most of the phellem. Narrow bands of lignified cells, often only one cell wide, frequently alternate with wider bands of the typical cells (fig. 13-12). The lignified cells appear somewhat sclerotic; the walls are thickened and pitted, but the cells retain their original shape. As Chang (1954) observed, walls of phellem cells are usually noticeably thicker in red oaks than in white oaks, often twice as thick (fig. 13-12). Howard found this to be generally true; but in red oaks some areas of phellem had quite thin walls, and a gradual increase in wall thickness across (toward outside of tree) the periderm was frequently observed.

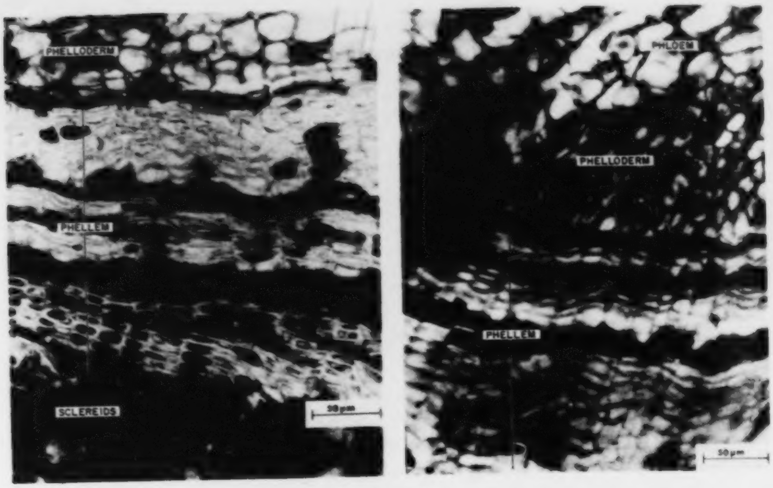


Figure 13-12.—Walls of phellem cells are considerably thicker in red oaks (left) than in white oaks (right). In both, narrow bands of lignified cells (dark lines) alternate with ordinary cork tissue. Tissues at lower edge of these micrographs are toward tree exterior, those at upper edge toward xylem.

Phelloderm, to the inside of the phellogen, is inconspicuous and resembles adjacent parenchyma. Only a few layers are present, generally six to eight cells or less, and these often cannot be distinguished from neighboring parenchyma unless their radial alignment is evident (figs. 13-12 right and 13-13); consequently, this inner portion of the periderm is often overlooked by many observers. The function of this tissue is uncertain (Howard 1977).

Secondary phloem—The secondary phloem is the tissue formed by the vascular cambium toward the exterior of the stem (fig. 13-8). This inner bark is the principal food-conducting tissue of the tree, transporting substances manufactured in the crown downward to other parts of the tree—primarily through sieve elements. The **conducting phloem,** in which sieve elements are functioning, is mostly restricted to the growth increment of the current year. The remaining secondary phloem with non-functioning sieve elements is **nonconducting phloem.**

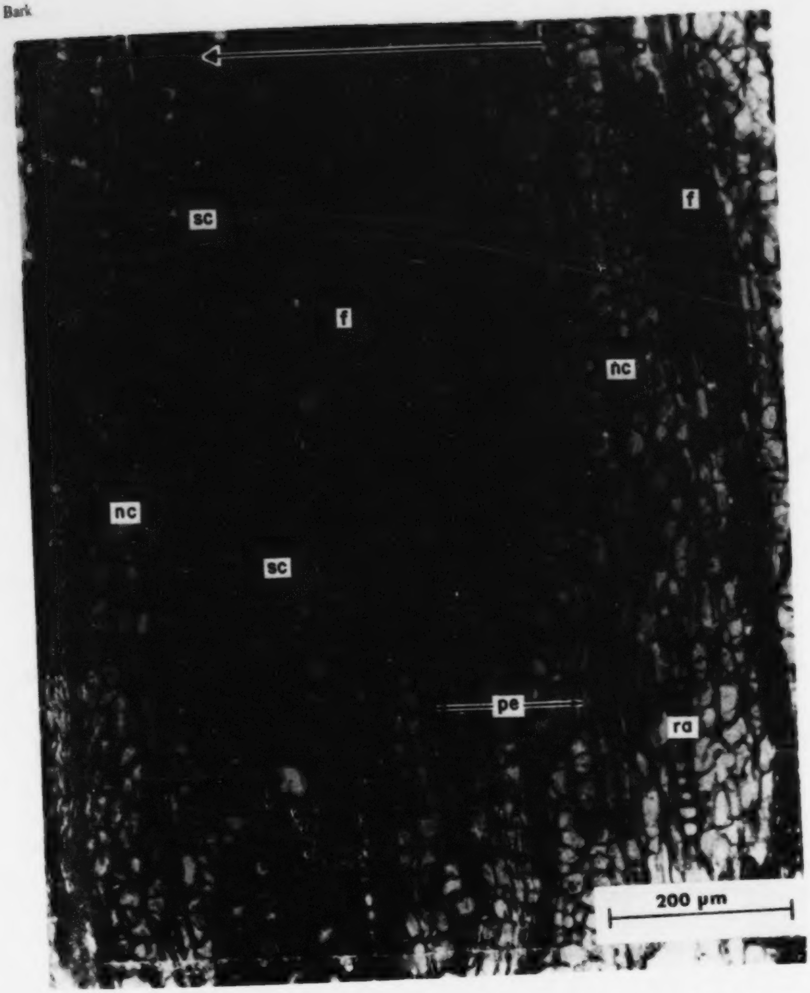


Figure 13-13.—Radial section of post oak bark. Arrow indicates exterior of tree. Fibers (f) accompanied by crystal-containing parenchyma, periderm (pe), old nonconducting phloem tissue (nc), narrow ray (ra) seen in end view after tissue collapse and distortion, sclereid groups (sc). (Photo from Howard 1977.)

Thickness of inner bark varies considerably with species (figs. 13-31 through 13-56). Howard (1977) noted that oaks have a fairly thick inner bark, generally 3 to 7 mm, but only a narrow band (about 200 to 300 µm, according to Huber (1958)) next to the cambium is active in conduction. When phloem ceases to function as conducting tissue, its structure becomes greatly modified. The thin-walled cells readily collapse and become distorted, and their arrangement disorganized; original tissue arrangement becomes indiscernible not far from the cambium. Most of the early collapse involves sieve-tube members and companion cells; parenchyma distortion occurs mainly after separation from the inner bark by a periderm. Only fibers and sclereids have rigid walls that resist distortion.

Sieve elements—Organic solutes are longitudinally conducted primarily by **sieve tubes,** which in hardwoods are comprised of a series of vertical **sieve elements** (fig. 13-9AB). Only those in a narrow zone next to the cambium actively conduct solutes, for most sieve tubes function one season only. Sieve tubes occur scattered singly, in groups, or in interrupted tangential bands. They rarely occur in actual contact with fibers or sclereids but are usually separated from them by parenchyma or companion cells (Zahur 1959). **Companion cells** (fig. 13-9AB), which have a close physiological relationship to sieve elements, collapse when sieve elements cease to function.

Cell walls of sieve elements are cellulosic, unlignified, and in many species very thin. In other species, however, sieve element cell walls have a distinct thickening called **nacreous thickening** or nacreous wall (Esau and Cheadle 1958). Such thickened walls, reacting positively to histochemical tests for cellulose and pectins (Esau 1965), generally shrink in the nonconducting phloem. In the 13 southern hardwoods studied by Nanko and Côté (1980), sweetbay (fig. 13-14) and yellow-poplar (fig. 13-57 left, see "n") had very thick nacreous walls, but those in American and winged elm were very thin. Nanko and Côté found that nacreous walls of these four species did not show birefringence under polarized light, indicating that they are not crystalline, i.e., not cellulosic.

In sweetbay, Nanko and Côté found cellulose microfibrils sparsely distributed in the nacreous wall (fig. 13-14). Nacreous walls of hardwood species seems to be different from those of *Pinus* sp. (Mahmood 1965; Chafe and Doohan 1972) which have much more packed microfibrils and show strong birefringence under polarized light.

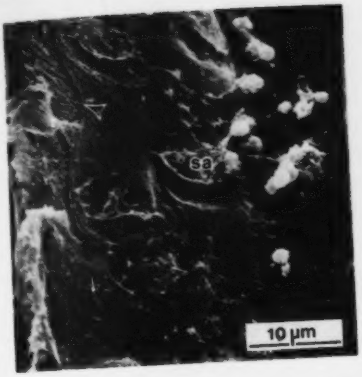


Figure 13-14.—Nacreous wall and sieve area (sa) of a sieve element in sweetbay, critical-point dried. Arrow indicates sparsely distributed microfibrils in the nacreous thickening. (Photo from Nanko and Côté 1980.)

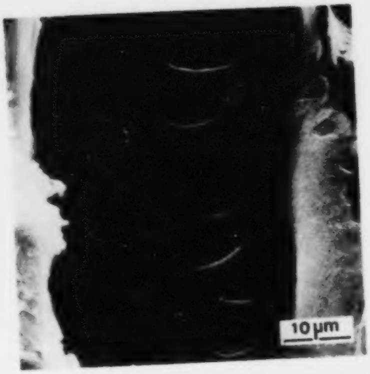


Figure 13-15.—Circular to oval sieve areas of the lateral wall of a sieve element in sweetbay. Freeze dried. (Photo from Nanko and Côté 1980.)

Sieve elements communicate with other cells and with each other through specialized cell-wall portions called **sieve areas** having clusters of perforations or pores through which connecting strands join adjacent sieve elements. Plasmodesmata connect the sieve areas with parenchyma cells (Esau 1965, 1969). During the functioning life of the sieve element, a deposit called callose builds up around each connecting strand and eventually over the whole sieve area. Callose usually disappears after conduction ceases; sieve areas then appear as thin areas with numerous tiny perforations. Sieve areas on lateral walls can be classified into two principal types according to their structure: those having circular to oval shape and those which exhibit a random network structure. The first type is found in American elm, winged elm, sweetbay (fig. 13-15), and yellow-poplar (figs. 13-18 and 13-57 top right). The second is found in white ash (fig. 13-16), green ash, hackberry, red maple, southern red oak, white oak, sweetgum, and black tupelo. Sieve elements of hickory have scalariform (ladderlike) sieve areas on lateral walls (fig. 13-43 lower left).

Sieve elements, arranged in vertical series to form sieve tubes, are interconnected at end-wall junctions by specialized sieve areas called **sieve plates** (Esau 1977), either compound or simple. **Compound sieve plates** with several sieve areas mostly in scalariform pattern, commonly on inclined end walls, were found by Nanko and Côté in white ash (fig. 13-17), green ash, hickory, southern red oak, white oak, sweetbay, sweetgum, black tupelo, and yellow-poplar (fig. 13-18). **Simple sieve plates,** considered more specialized by Esau (1977), were found by Nanko and Côté in American elm (fig. 13-19), winged elm, hackberry, and red maple.

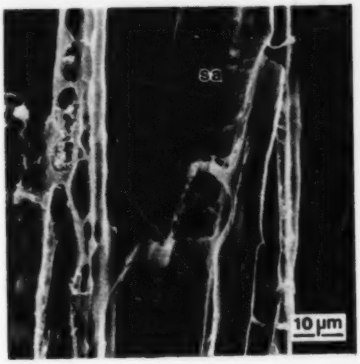


Figure 13-16.—Random-network sieve areas (sa) in the lateral wall of a sieve element in white ash. (Photo from Nanko and Côté 1980.)

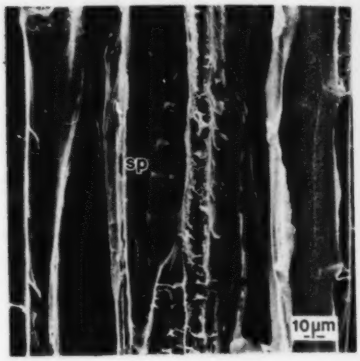


Figure 13-17.—Compound sieve plate (sp) in inclined end wall of a nonconducting sieve element in white ash. (Photo from Nanko and Côté 1980.)

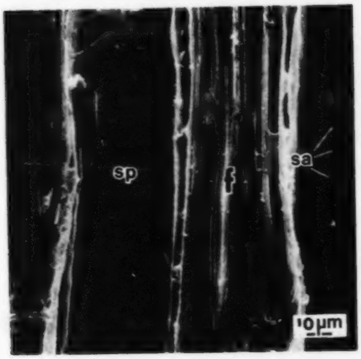


Figure 13-18.—Compound sieve plate (sp) in inclined end wall, and sieve areas (sa) of nonconducting sieve elements adjacent to fiber (f) in yellow-poplar. (Photo from Nanko and Côté 1980.)

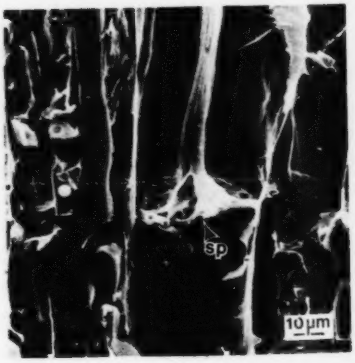


Figure 13-19.—Simple sieve plate (sp) of conducting sieve element in American elm. Strand of viscous protein-rich slime evident above sieve plate. (Photo from Nanko and Côté 1980.)

Howard (1977) found sieve tube elements in oaks difficult to study because outside the narrow conducting zone they are nearly transparent; in cross section they could be distinguished from parenchyma only if the end sieve plates were in view.

Readers interested in early studies of the structure of sieve elements in white ash, American elm, hickory, yellow-poplar, white oak, and black tupelo, should consult MacDaniels (1918). Additionally, Evert et al. (1969) reported on the ontogeny and structure of sieve elements in American elm.

Hiroki Nanko (unpublished data related to Nanko and Côté (1980)) found that the length of sieve elements in 6-inch trees of four species measured as follows:

Species	Average	Range	Standard deviation
	μm		
Ash, green	342	240-480	44
Ash, white			
Tree No. 1	338	290-390	30
Tree No. 2	381	290-450	36
Hackberry	303	200-440	46
Sweetgum	976	480-2,020	275

Phloem parenchyma.—Parenchyma of phloem is arranged in two systems: longitudinal (primarily in strands) and horizontal (rays). Abundance of longitudinal parenchyma varies with species and with the environment (Zahur 1959). In the southern red oaks such cells are fairly abundant, irregularly distributed among sieve tubes or in tangential bands in undistorted tissues (Howard 1977). Figures 13-31 through 13-57 illustate the distribution and character of longitudinal parenchyma (pa) in transverse sections of southern red and white oaks and in 13 non-oak hardwoods.

Phloem parenchyma cells are roughly cylindrical in cross section and usually have thin cellulosic walls. They communicate with each other and with ray cells through pit fields in primary walls; Nanko and Côté (1980) found such primary pit fields—deeply depressed (fig. 13-20). Phloem parenchyma cells contain stored products such as tannins and other phenolic compounds, starches, oils, fats, and various types of crystals. Parenchyma remain functional long after the sieve elements die; some parenchyma cells, acquiring thick secondary walls, become modified as sclereids (Howard 1977).

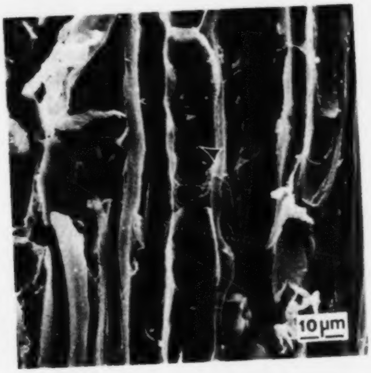


Figure 13-20.—Primary pit fields (arrow) in axial parenchyma cells of American elm. (Photo from Nanko and Côté 1980.)

Phloem rays.—Phloem rays (fig. 13-11 H and K) provide horizontal conduction within the inner bark. They transport nutrients from the actively conducting zone to living parenchyma and the innermost phellogen. The outer portions of rays die when eventually sealed off by formation of a new and deeper periderm.

When bark of oaks and some other species is split from the wood at or near the cambium, rays are readily visible on, and usually protrude from, the inner surface of the phloem (fig. 13-7). These bark rays are the outward continuation of the wood rays, and like them, occur in two distinct sizes in oaks, narrow rays (uniseriate or partially biseriate) and broad, multiseriate rays. In oaks they are homocellular, i.e., comprised of only procumbent ray cells that are usually rather short and thin-walled.

Many ray cells in bark are modified to become sclereids. They develop thick, lignified secondary walls with numerous simple pits and sometimes change in shape. The sclerification process begins near the cambium and increases as the cells are pushed outward.

Because of the functional and structural changes occurring in the bark and the resulting physical stresses, the rays may become distorted in nonfunctioning phloem and the outer bark. Some rays dilate by multiplication of cells within the ray, producing an archlike pattern in the outer portion of the inner bark.

Companion cells.—Companion cells (fig. 13-9AB) are narrow, highly specialized parenchymatous cells, intimately associated with sieve elements. They are produced by the same cambial cell that produced the accompanying sieve tube member. The two types of cells die and collapse simultaneously; they often remain attached in macerated material. In the oaks studied by Howard (1977) companion cells were often difficult to distinguish from ordinary parenchyma by light microscopy.

Fibers and other sclerenchyma cells.—Sclerenchyma cells, longitudinally oriented and generally with thick lignified walls, provide the mechanical strength of bark. Holdheide (1951), Zahur (1959), and Evert (1963) identified three types of sclerenchyma cells in the secondary phloem as follows: phloem fibers, fiber sclereids, and sclereids (fig. 13-9). **Phloem fibers,** derived directly from fusiform cambial initials, generally undergo intrusive growth and mature in the conducting phloem. **Fiber-sclereids** originate from parenchyma cells within the nonconducting phloem, also undergo intrusive growth, and at maturity become long slender elements mostly indistinguishable from phloem fibers—the only other greatly elongated cells in bark (fig. 13-10 and 13-11C). **Sclereids** develop mostly in nonconducting phloem and derive from parenchyma cells by secondary modification; they are thick-walled but short (fig. 13-11D).

Cell wall structure of fibers in bark.—Phloem fibers and fiber-sclereids do not have the $S_1 + S_2 + S_3$ structure (fig. 5-73) basic to wood tracheids and libriform fibers in hardwood (Holdheide 1951), and their structure varies with genera and sometimes species of trees.

From study of 45 hardwood species representing 30 genera, Nanko (1979) categorized cell wall structure of phloem fibers and fiber-sclereids of most hardwood species into two types (fig. 13-21) as follows:

(1) S1 + S2 type.
(2) S1 + S2 + G (gelatinous layer) type.

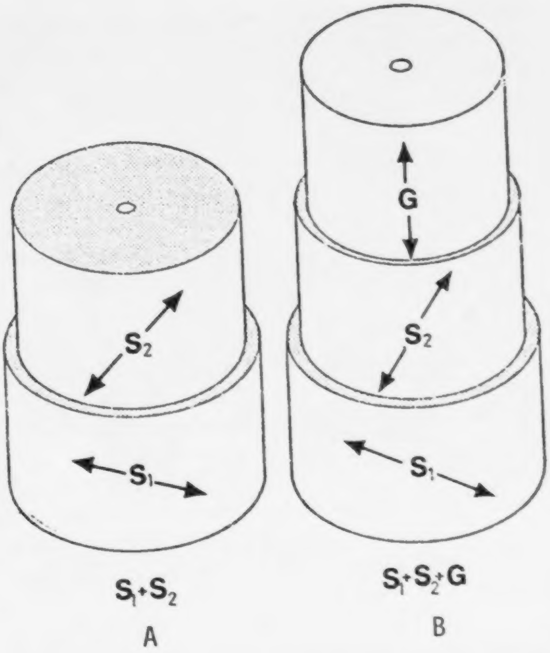


Figure 13-21.—Diagrammatic representation of cell wall organization of phloem-fibers and fiber-sclereids. Arrows indicate alignment of cellulose microfibrils (Nanko 1979). S1, S2, and S3 refer to layers of the secondary wall in both xylem and phloem cells (i.e., wood and bark). S1 refers to the outer layer of the secondary wall; S2 is the middle layer; and S3 is the inner layer normally lining the cell cavity or lumen of xylem tissue, but not present in phloem fibers. In reaction tissue of xylem a "G-layer" often appears in place of the S3 or the S2. The term G-layer refers to the gelatinous layer because of the gel-like, swollen nature of this region. G-layers were found in normal bark by Nanko and Côté (1980). (Drawing after Nanko and Côté 1980.)

Fibers of S1 + S2 type are more common than the other. They possess very thick and lignified secondary walls, and their lumina are almost occluded. The secondary wall consists of two layers, a thin outer layer, S1, and the thicker inner layer, S2. The microfibrils of S1 make a large angle and those of S2 a small angle with the fiber axis. Microfibrils in the two layers form opposed helices (fig. 13-21A); that is, one exhibits a Z helix and the other an S helix.

Fibers of the S1 + S2 + G type have lignified outer layers S1 and S2 but also an unlignified innermost layer G (gelatinous layer). The microfibril orientation of the outer two layers is the same as that of the S1 and S2 layers of S1 + S2 type fibers. The innermost layer, like that of the gelatinous layer of tension wood fibers, is virtually unlignified and its microfibrils are oriented (fig. 13-21B) parallel to the fiber axis. Fibers of this type are usually observed in the secondary phloem adjacent to normal cells. Their structure, therefore, is not caused by the stress reaction phenomenon causing tension wood formation in hardwoods.

All of the thirteen hardwood species studied by Nanko and Côté (1980) have phloem fibers or fiber-sclereids, of one or both of the types mentioned above.

Nanko and Côté (1980) found that southern hardwoods whose fibers have S1 + S2 structure include sweetbay (fig. 13-22 left), sweetgum, green ash, white ash, red maple, yellow-poplar, and black tupelo. Nanko (1978, 1979) reported this type of fiber is also found in *Populus euromericana* Guinier, *Prunus jamasakura* Sieb., *Magnolia obovata* Thunb., *Magnolia salicifolia* (Sieb. & Zucc.) Maxim., *Acer crataegifolium* Sieb. & Zucc., and *Acer rufinerve* Sieb. & Zucc.

Fibers with S1 + S2 + G structure are found in American elm (fig. 13-22 right), winged elm, hackberry (fig. 13-23 left), hickory (figs. 13-23 right and 13-24). Figure 13-24 is a longitudinal-oblique section of a phloem fiber of hickory showing the microfibril orientation in S1, S2, and G. The lignification of the S1 and S2 layers of the phloem fibers of hickory and hackberry is quite weak in comparison with American elm (figs. 13-22 right and 13-23). According to Howard (1977), R. F. Evert, in a personal communication, has suggested that phloem fibers in oak are gelatinous. In white oak and southern red oak phloem fibers have S1 + S2 + G structure (fig. 13-25 left), perhaps due to the reaction phenomenon, but they occasionally have phloem fibers of the S1 + S2 type also (fig. 13-25 right). The gelatinous layer of those species is faintly lignified (fig. 13-25 left). Nanko (1979) reported that in seven other species of *Quercus* the phloem fibers have the S1 + S2 structure.

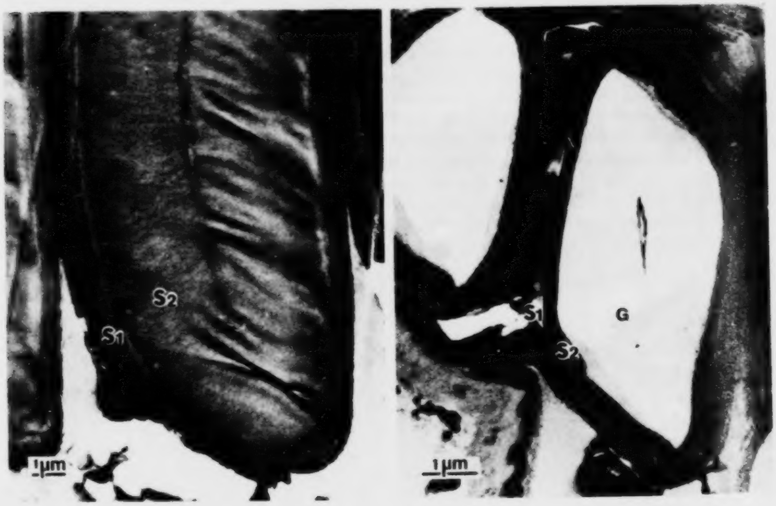


Figure 13-22.—Transverse sections of phloem fibers; TEM, stained with $KMnO_4$. (Left) Sweetbay with S1 + S2 layers only. (Right) American elm with S1 + S2 + G layers. (Photos from Nanko and Côté 1980.)

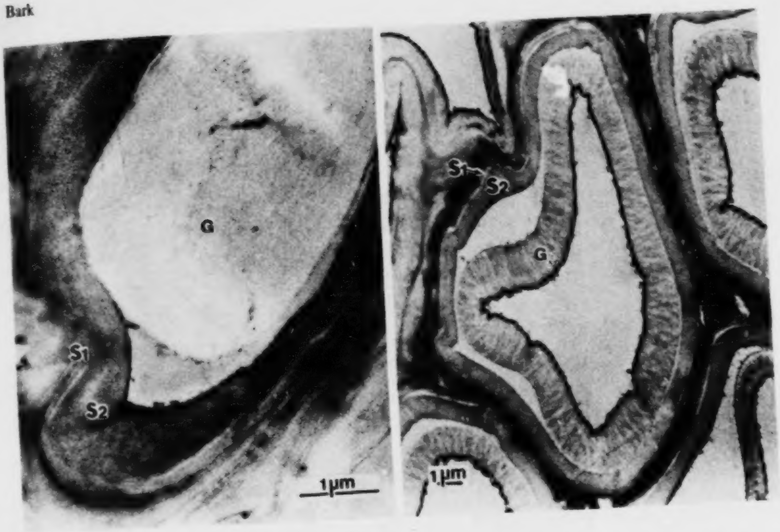

G
S1
S2
1µm
S1
S2
G
1µm

Figure 13-23.—Transverse sections of phloem fibers; TEM, stained with $KMnO_4$. (Left) Hackberry. (Right) Hickory. (Photos from Nanko and Côté 1980.)

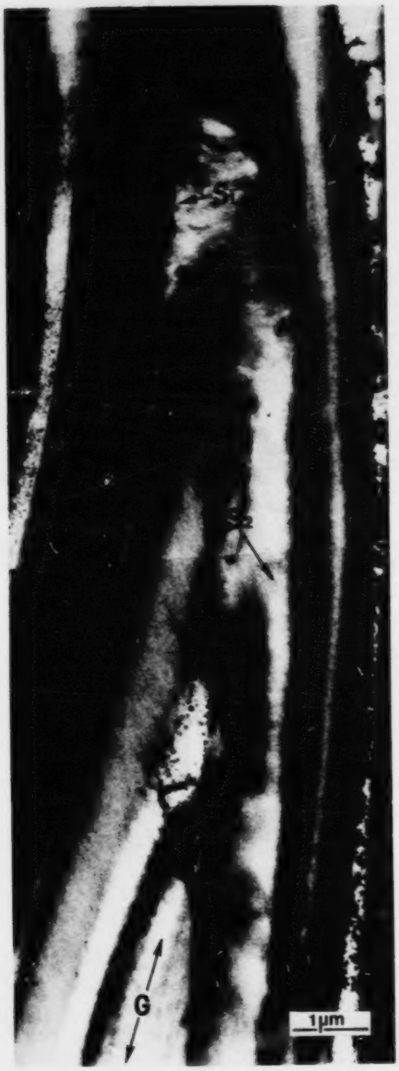


Figure 13-24.—Longitudinal oblique section of a phloem fiber in hickory; arrows show the microfibril orientation in each layer; TEM, stained with $KMnO_4$. (Photo from Nanko and Côté 1980.)

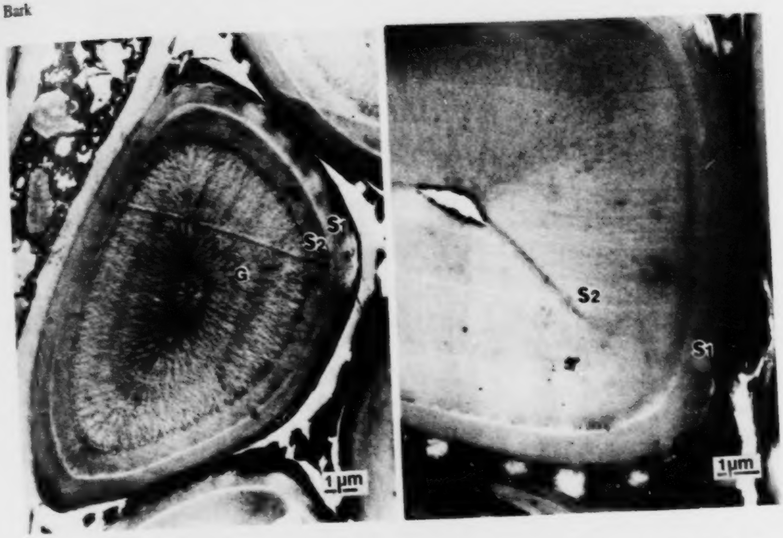


Figure 13-25.—Transverse sections of oak phloem fibers; TEM stained with $KMnO_4$. (Left) Southern red oak with S1 + S2 + G cell wall layers. (Right) White oak with S1 + S2 cell wall layers. (Photos from Nanko and Côté 1980.)

Fiber dimensions.—Figures 13-22 through 13-25 and 13-31 through 13-57 illustrate fiber dimensions observed by Nanko and Côté (1980) in bark of 13 southern hardwoods; their data are summarized in table 13-1. In their study the fibers were macerated with Jeffrey's solution or by the kraft pulping method, stained and mounted on slides, and measured for length on a projected large image. Average fiber lengths observed varied from 641 µm in red maple to 1,939 µm in hackberry (table 13-1). Diameters were small in red maple and hackberry (10 to 15 µm), and largest in sweetgum (35 to 45 µm).

TABLE 13-1—*Fiber dimensions observed by Nanko and Côté (1980) in secondary phloem of 6-inch trees of 13 southern hardwood species*

Species	Mean length	Range in length	Standard deviation, length	Diameter[1]
	-----	-----	µm	-----
Ash, green	1,000	380-1,430	—	20 x 30
Ash, white	1,004	270-1,360	431	20 x 30
Elm, American	1,280	480-1,980	362	15 x 17
Elm, winged	833	380-1,610	254	15 x 17
Hackberry	1,989	510-3,450	698	10 x 12
Hickory, sp.	1,179	600-1,750	199	10 x 25
Maple, red	641	240- 950	192	10 x 15
Oak, southern red	902	420-1,340	253	—
Oak, white	883	430-1,080	130	10 x 17
Sweetbay	1,041	420-1,430	244	15 x 25
Sweetgum	783	120-1,380	289	35 x 45
Tupelo, black	—	—	—	20 x 25
Yellow-poplar	1,030	360-1,700	275	8 x 30 (or 20 x 25)[2]

[1] Usually narrow in radial direction.

[2] Somewhat expanded in radial direction.

Data taken by F. G. Manwiller in a systematic sampling of fibers to statistically represent entire stembark of 6-inch, pine-site hardwoods of 22 species are summarized in table 13-2. See table 3-1 for tree dbh, age, height, and weight. Manwiller's data indicate that stem-average lengths were shortest in scarlet and blackjack oaks (0.81 mm) and longest in hackberry (1.32 mm). Bark fiber radial diameters averaged least in winged elm (8.49 µm) and greatest in sweetgum (24.23 µm). Average tangential wall thickness was least in winged elm (3.26 µm) and greatest in sweetgum (11.05 µm). Lumen radial diameter averaged greatest in yellow-poplar (5.77 µm); all the other species had lumen diameters from 1.83 (American elm) to 3.04 µm (hackberry). Branch bark fiber dimensions sampled from the same trees are given in table 13-3; average dimensions were not greatly different from those of stembark, as follows:

Fiber dimension	Stembark	Branchbark
	----- µm	-----
Length	985	966
Radial diameter	17.86	15.12
Tangential wall thickness	7.69	6.30
Lumen radial diameter	2.45	2.50

In Manwiller's study, variability in length of bark fibers was similar to that among wood fibers. Within-tree standard deviation averaged 0.247 mm for stem bark fibers and 0.278 mm for branch bark fibers. This average is about 2.5 times the variability among trees of a species, where one standard deviation averaged 0.101 mm for stem bark fibers and 0.108 mm for branch bark.

Bark fibers in the stump-root system of these pine-site hardwoods average longer (1.22 mm), larger in radial diameter (20.68 µm) but have about the same tangential wall thickness (7.80 µm) compared to fibers from stembark and branchbark. See table 14-6.

TABLE 13-2—*Fiber length and fiber transverse dimensions of stembark from 6-inch trees of 22 species of hardwoods grown on southern pine sites*[1,2]

Species	Fiber length	Fiber radial diameter	Tangential wall thickness	Lumen Radial diameter
	mm	*µm*		
Ash, green	1.15 (.10)	21.20 (3.21)	9.45 (1.59)	2.30 (.24)
Ash, white	1.17 (.10)	21.07 (2.62)	9.37 (1.36)	2.32 (.22)
Elm, American	1.07 (.18)	10.56 (.93)	4.37 (.40)	1.83 (.34)
Elm, winged	.83 (.11)	8.49 (1.34)	3.26 (.57)	1.94 (.40)
Hackberry[3]	1.32 (.23)	11.82 (2.02)	4.39 (.68)	3.04 (1.48)
Hickory	1.18 (.20)	13.99 (1.50)	5.81 (.91)	2.37 (.63)
Maple, red	.84 (.10)	15.62 (1.42)	6.54 (.54)	2.51 (.52)
Oak, black	.94 (.07)	18.37 (1.42)	7.95 (.87)	2.34 (.50)
Oak, blackjack	.81 (.04)	19.68 (1.58)	8.78 (.81)	2.13 (.23)
Oak, cherrybark	.94 (.06)	19.06 (1.43)	8.42 (.69)	2.23 (.29)
Oak, laurel	.87 (.04)	18.39 (1.06)	8.06 (.46)	2.26 (.34)
Oak, northern red	.95 (.09)	18.92 (2.41)	8.37 (1.25)	2.19 (.19)
Oak, post	.85 (.09)	16.92 (.64)	7.44 (.32)	2.04 (.19)
Oak, scarlet	.81 (.10)	18.95 (2.36)	8.29 (1.19)	2.33 (.32)
Oak, Shumard	.92 (.06)	18.99 (.60)	8.41 (.37)	2.17 (.25)
Oak, southern red	.90 (.05)	19.40 (.73)	8.46 (.33)	2.50 (.26)
Oak, water	.89 (.09)	18.76 (1.08)	8.23 (.52)	2.31 (.30)
Oak, white	.91 (.08)	17.18 (.96)	7.39 (.49)	2.21 (.39)
Sweetbay	.95 (.12)	18.47 (1.35)	7.93 (.57)	2.60 (.34)
Sweetgum	.96 (.09)	24.23 (3.41)	11.05 (1.63)	2.14 (.27)
Tupelo, black	1.18 (.10)	22.82 (2.84)	10.22 (1.46)	2.39 (.28)
Yellow-poplar	1.24 (.14)	19.96 (2.24)	7.09 (.54)	5.77 (2.06)

[1] The first value is the average for 10 trees; the second value (in parentheses) is the within-species standard deviation.

[2] Manwiller, F. G. Unpublished data in Study File FS-SO-3201-1.42, U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Pineville, La.

[3] Mostly sugarberry.

TABLE 13-3—*Fiber length and fiber transverse dimensions of branchbark from 6-inch trees of 22 species of hardwoods grown on southern pine sites*[1,2]

Species	Fiber length	Fiber radial diameter	Tangential wall thickness	Lumen Radial diameter
	mm	----------	*µm*	----------
Ash, green	1.10 (.10)	19.23 (3.50)	8.47 (1.76)	2.30 (.64)
Ash, white	1.12 (.12)	19.91 (2.36)	8.99 (1.07)	1.92 (.46)
Elm, American	1.36 (.29)	10.12 (.76)	4.05 (.56)	2.02 (.55)
Elm, winged	1.10 (.13)	7.76 (1.82)	2.99 (.69)	1.75 (.55)
Hackberry[3]	1.44 (.26)	10.60 (.67)	3.95 (.21)	2.62 (.56)
Hickory	1.16 (.12)	13.06 (.92)	5.33 (.56)	2.41 (.85)
Maple, red	.85 (.11)	15.13 (2.35)	6.30 (1.09)	2.52 (.56)
Oak, black	.84 (.08)	15.34 (1.20)	6.52 (.59)	2.30 (.50)
Oak, blackjack	.77 (.07)	16.39 (.79)	7.06 (.55)	2.26 (.55)
Oak, cherrybark	.88 (.09)	15.50 (.99)	6.57 (.69)	2.36 (.71)
Oak, laurel	.88 (.09)	15.66 (1.00)	6.48 (.30)	2.70 (.69)
Oak, northern red	.80 (.07)	15.29 (1.41)	6.44 (.81)	2.41 (.42)
Oak, post	.72 (.07)	14.38 (.71)	6.32 (.35)	1.75 (.35)
Oak, scarlet	.79 (.08)	15.52 (1.17)	6.45 (.53)	2.61 (.57)
Oak, Shumard	.88 (.07)	15.34 (.89)	5.99 (.65)	2.77 (.45)
Oak, southern red	.80 (.04)	15.18 (1.20)	6.50 (.61)	2.18 (.48)
Oak, water	.81 (.08)	15.20 (1.10)	6.10 (.79)	2.93 (.85)
Oak, white	.80 (.05)	13.97 (1.44)	5.89 (.79)	2.17 (.36)
Sweetbay	.82 (.08)	16.15 (1.70)	6.56 (.67)	3.08 (.51)
Sweetgum	1.14 (.12)	17.88 (2.46)	7.38 (1.31)	3.13 (1.26)
Tupelo, black	1.15 (.16)	18.83 (1.71)	7.68 (.89)	3.46 (1.91)
Yellow-poplar	1.04 (.11)	16.26 (1.93)	6.47 (.45)	3.32 (1.88)

[1] The first value is the average for 10 trees; the second value (in parentheses) is the among-tree standard deviation.

[2] Manwiller, F. G. Unpublished data in Study File FS-SO-3201-1.42, U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Pineville, La.

[3] Mostly sugarberry.

Ezell and Stewart (1978) measured fiber lengths in nine upland and nine bottomland sweetgum trees and found that stembark averages (numerical averages based on all heights in each tree) varied among trees from 0.96 to 1.44 mm. Generally, but not always, bark fibers from bottomland sweetgum trees were longer than those from upland sweetgum.

Sclereids.—As noted previously, sclereids (figs. 13-9D, 13-10, and 13-11D) develop mostly in nonconducting phloem and derive from parenchyma cells by secondary modification. These thick-walled, lignified, short, dense cells lend rigidity, hardness and brittleness to bark and are responsible for some processing problems when bark is included in fine papers, e.g., "fisheyes" in calendered papers and pin holes in coatings. Sclereid cell walls have distinct lamellate layers with numerous simple pits (Howard 1977). Howard found that in bark of pine-site oaks these hard irregular cells—frequently called stone cells—are grouped into compact masses readily visible on cut surfaces of both inner and outer bark (figs. 13-7 and 13-13); on cross sections of oak bark they appear as shiny spots that form short tangential bands. Readers needing additional information on cell wall structure of sclereids should consult Mia (1969), Parameswaran (1975), Wardrop (1976), and Nanko (1978).

CRYSTALS AND OTHER INCLUSIONS

Crystals, common inclusions in phloem elements, were found by Nanko and Côté (1980) in all 11 non-oaks and both oaks studied. In the 11 southern oaks she studied, Howard (1977) found strands of crystal-bearing parenchyma along margins of widely spaced and discontinuous fiber bands composed of small fiber groups usually two to five cells wide.

These crystals vary in form, but are mainly calcium oxylate. Frey (1925) categorized calcium oxalate crystals into monohydrate and trihydrate types. Frey-Wyssling and Blank (1938) suggested that monohydrate calcium oxalate crystals have forms of styloids and raphides or make twins, depending on the growing environment. Holdheide (1951) concluded that calcium oxalate crystals are always monohydrate, and they can take the form of druses, single crystals, and crystal sands. The various crystals in wood tissue have been observed in the scanning electron microscope by several authors (Hirata et al. 1973; Scurfield et al. 1973; Gray 1974), but observations of crystals contained in phloem are rare. Application of energy dispersive X-ray microanalysis (EDXA) to the crystals and silica was tried by Gray and Côté (1974) and Core et al. (1979). Gray and Côté (1974) suggested the utility of scanning electron microscopy with EDXA devices to identify elements and illustrate their distribution; see also Postek et al. (1980) and Woldseth (1973).

The phloem parenchyma of winged elm and American elm contain crystals (fig. 13-26) of a type common in phloem (Holdheide 1951; Nanko et al. 1976). They appear to be twin crystals of monohydrate calcium oxalate (Frey-Wyssling and Blank 1938; Holdheide 1951). The crystals at A and B in figure 13-26 consist of similar single crystals, but are differently joined, as suggested by Holdheide (1951). Such crystals are often covered with a thin sheath. In the same cell containing twin crystals, very tiny crystals of different shape are found (fig. 13-26) firmly attached to the cell wall.

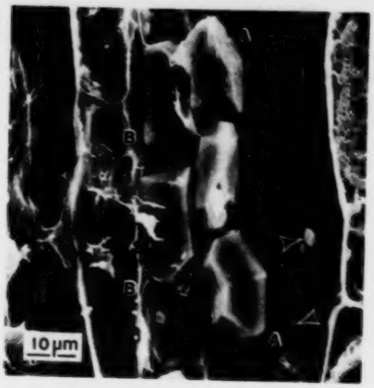


Figure 13-26.—Twin crystals A and B in winged elm are each comprised of identical single crystals, but the single crystals are joined differently so that A and B differ in shape. Arrows indicate small crystals contained in the same cell. (Photo from Nanko and Côté 1980.)

The chambered crystalliferous cells associated with the phloem fibers of white oak also contain calcium oxalate crystals of twin crystal type, the crystals being completely surrounded by the thick sheath of the secondary wall (fig. 13-27 top right). Nanko et al. (1976) studied development of the secondary wall surrounding crystals in sclerified cells of *Populus*. They found that crystals grow in vacuoles and that a secondary-wall type of cellulosic sheath formed over the crystal surface before the vacuole is absorbed or reduced.

In addition to the twin crystals commonly observed, many others occur in the phloem of southern hardwoods. **Tiny crystals,** nearly filling the lumens of ray and axial parenchyma cells, are found in white ash (fig. 13-27 bottom left) and green ash. In phloem parenchyma of hickory **styloid crystals** covered by a thin sheath (fig. 13-27 bottom right) have a shape similar to the calcium oxylate monohydrate crystals found in *Terminalia belerica* Roxb. by Scurfield et al. (1973). **Druse crystals** (fig. 13-27 top left), covered by a thin sheath, are found in phloem parenchyma of white oak; the parenchyma cells containing such crystals are divided into small compartments by cell walls having many pores. The **large rhombic crystals** of sweetgum (fig. 13-28) are variable in shape and covered with a thin sheath; some form twins.

Nanko and Côté (1980) found **crystal-containing sclerified cells** in white oak (fig. 13-29) and sweetgum. Lamellation of alternating bands of electron-dense and electron-transparent tissue in the thick secondary wall surrounding the crystals was found by Nanko et al. (1977), through study of *Populus*, to result from sequential shifts in microfibril orientation. The angle at which the cell walls were cut yielded variable electron density reflecting the changes in microfibril inclination angle.

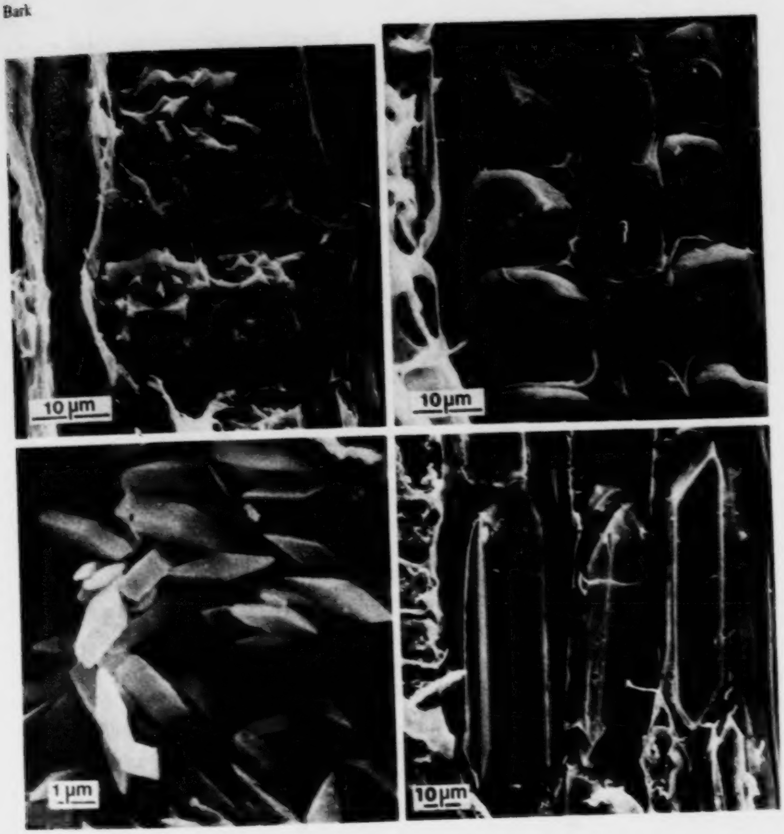


Figure 13-27.—Crystals in bark. (Top left) Druse crystals in phloem parenchyma of white oak. (Top right) Chambered crystaliferous cells of white oak associated with a phloem fiber (f). (Bottom left) Small crystals in ray parenchyma cells of white ash. (Bottom right) Styloid crystals in parenchyma strands of hickory. (Photo from Nanko and Côté 1980.)

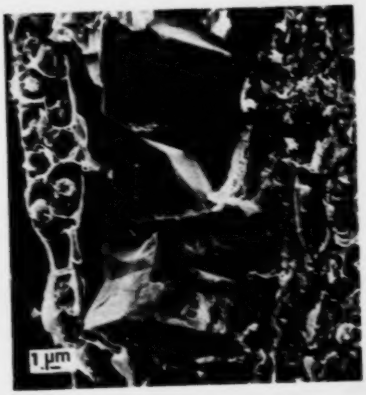


Figure 13-28.—Large rhombic crystals of sweetgum. (Photo from Nanko and Côté 1980.)

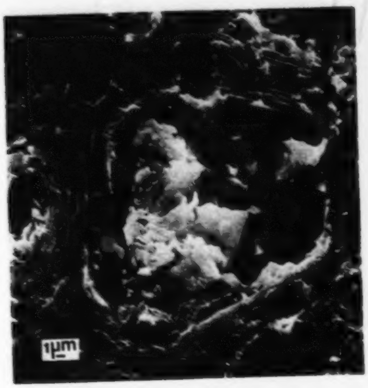


Figure 13-29.—Crystal-containing sclerified cells of white oak. (Photo from Nanko and Côté 1980.)

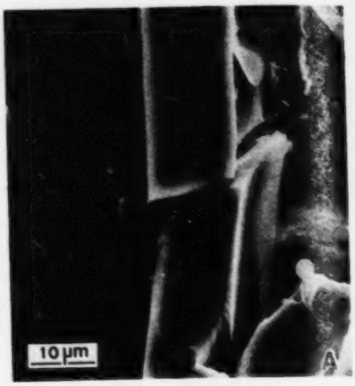


Figure 13-30.—Silicon substance filling the lumen of a thin-walled fiber in sweetbay. (Photo from Nanko and Côté 1980.)

The EDXA spectrum of crystals depicted in figures 13-26 through 13-29 indicate a high concentration of calcium. In American elm small amounts of silica are often detected on crystal surfaces.

Inclusions of the bark do not always contain calcium. Nanko and Côté (1980) found a compound of barium and sulfur in the ray and axial parenchyma of green and white ash. In secondary phloem of sweetbay they found a glasslike amorphous silica substance (fig. 13-30) filling the lumina of thin-walled fibers in the tangential bands of phloem (fig. 13-51 bottom right); X-ray analyses suggested that the substance—which extensively damaged microtome knife edges—was SiO_2.

Rhytidome contains an abundance of deposited materials that provide its dark coloration. These dark reddish-brown deposits—mainly phenolic substances such as tannins and phlobaphenes—are found primarily in parenchyma and crushed sieve tubes. These materials may act as anti-oxidants and inhibitors of fungal attack (Srivastava 1964; Somers and Harrison 1967). Their value in tanning leather has long been recognized, and they are considered a possible source of phenolics for adhesives.

SPECIES DESCRIPTIONS

General bark structure and cellular arrangement in the secondary phloem of the 11 non-oaks and white and southern red oak studied by Nanko and Côté (1980) are shown in figures 13-31 through 13-57; they are discussed below in alphabetical order by species common name.

From her study of the bark of 11 oaks found where southern pines grow, Howard (1977) concluded that their bark surface characteristics can be of supplementary value in their identification. The exterior surface of white oak bark is usually lighter in color than that of other oaks.

Most oaks have rough bark with longitudinal furrows and ridges; but laurel, water, and white oaks usually have relatively smooth bark. Smooth bark is also found on young growth, on upper stems and branches, and on some individual trees of high growth rate. Of the small-diameter trees examined, blackjack, post, and southern red oaks had thick bark; the laurel, cherrybark, water, and white oak samples were usually thin-barked. Other species were either intermediate in thickness or showed considerable variation. Southern upland oaks of small diameter generally have fibrous, stringy bark. Bark from most red oaks is hard and friable when cut across the grain, but the outer bark of white and post oaks tend to be soft and flaky, due probably to differences in the amounts of sclereids present.

Bark surface characteristics, however, are not totally reliable for species identification since they can be greatly modified by the environmental influences, and vary greatly within species (fig. 12-42 through 12-44). Gross features such as bark thickness, proportion of inner and outer bark, scaliness, and depth of fissures depend to a great degree on tree vigor and growth rate, age, and height on the tree. Guttenberg's (1951) photographs demonstrate the marked increase in oak bark roughness with decline in tree vigor.

Anatomical differences in oak bark offer some additional help in identifying species. As noted by Chang (1954), cork cells of white oaks generally have thinner walls than those of red oaks. White oaks retain their original phloem structure to a greater degree than red oaks. White oak rays are generally evident in a straight course past periderms. Chang (1954) considered an archlike pattern in older phloem as a characteristic of red oaks, but Howard (1977) found such patterns frequently in the white oaks as well.

Other characteristics given by Chang (1954) as general differences between the two groups were not confirmed by Howard's (1977) study. These included his comparison of inner to outer bark thickness, and the description of periderms and sclerenchyma as being in distinct tangential alignment in white oaks (in contrast to a loose irregular arrangement in red oaks). She found both arrangements in both groups of oaks; bark thickness was far too variable in these samples to serve as a distinguishing characteristic between the two groups.

Inner bark of black oak is bright gold when freshly cut, but the color may not be found in dry samples. No other characteristic was found that would, with certainty, identify an individual tree as a member of a particular oak species.

Ash, green.—The structure of green ash and white ash bark (fig. 13-31 and 13-32) is very similar. Bark of the trunk at breast height in trees 10 to 15 cm in diameter is about 5 to 7 mm thick in dry condition. Inner bark is 1.5 to 2.5 mm thick, almost the same as that of white ash; the outer bark is 3 to 5 mm thick, somewhat thinner than in white ash. Outer bark often has longitudinal fissures. Bark color varies from light brown to grayish brown (fig. 13-1 top left).

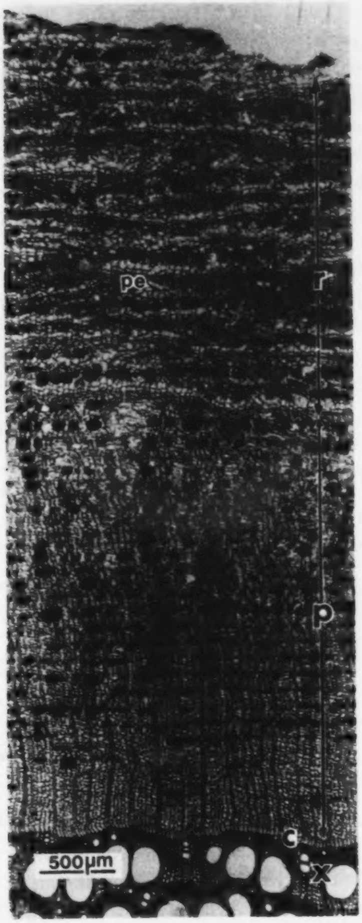


Figure 13-31.—Green ash. Transverse section of entire bark; p, secondary phloem; r, rhytidome; pe, periderm; c, cambium; x, xylem. (Photo from Nanko and Côté 1980.)

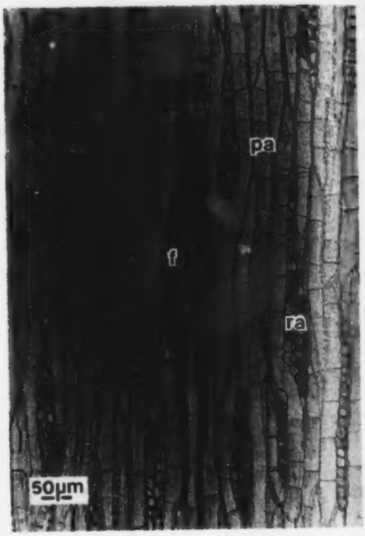


Figure 13-32.—Green ash. Tangential section of the nonconducting phloem; f, fiber; pa, phloem parenchyma; ra, ray. (Photo from Nanko and Côté 1980.)

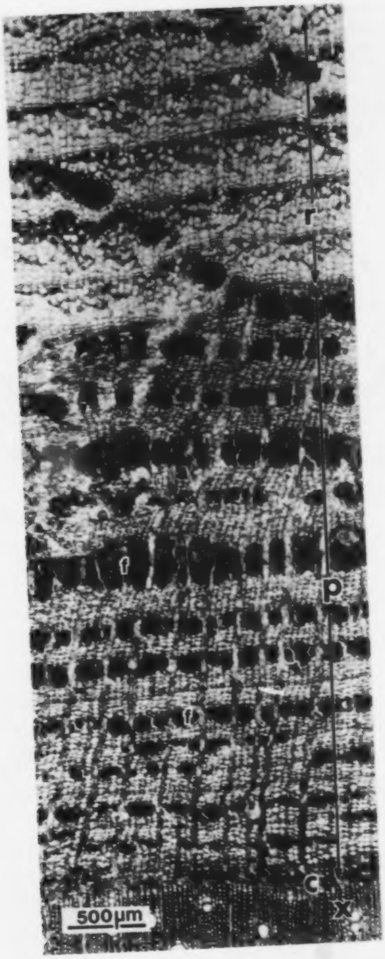
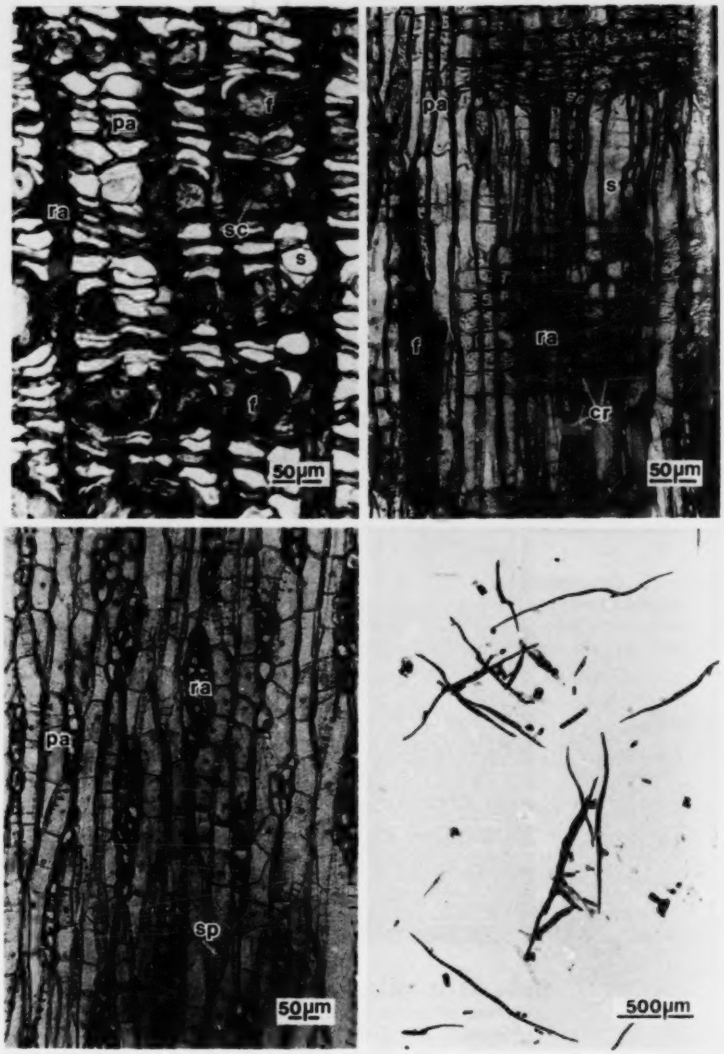


Figure 13-33.—White ash. Transverse section of entire bark; p, secondary phloem; r, rhytidome; f, fiber; c, cambium; x, xylem. (Photo from Nanko and Côté 1980.)

Minute anatomy is similar to that of white ash (figs. 13-33 and 13-34). Bark fibers in small trees average 20 x 30 µm in cross section and 1.00 to 1.15 mm long (tables 13-1 through 13-3).

Ash, white.—Bark at breast height (10 to 15 cm tree diameter) is rather thick and corky, and light brown in color (fig. 13-1 top right). It often has deep fissures. The total thickness of the bark varies from 6 to 14 mm, of which 2 to 3 mm is inner bark. Outer bark varies from 4 to 11 mm according to the development of corky tissue (fig. 13-33).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cr
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Figure 13-34.—White ash secondary phloem. (Top left) Transverse section. (Top right) Radial section showing small (cr) crystals in the (ra) ray cells and (pa) phloem parenchyma. (Bottom left) Tangential section. (Bottom right) Macerated fibers. Symbols: f, fibers; sc, sclereid; s, sieve element; sp, sieve plate. (Photos from Nanko and Côté 1980.)

In the secondary phloem sieve elements and parenchyma strands tend to differentiate alternately (fig. 13-34 top left), but two or three cells of sieve elements or parenchyma strands are often arranged successively in radial rows. Fibers are aligned tangentially (fig. 13-33). Sclereids are aligned with fiber bands.

Sieve elements have inclined compound sieve plates with 6 to 10 sieve areas (fig. 13-34 top right and bottom left). Sieve areas on the lateral walls have slightly specialized network structure. The expansion of sieve elements is rather small and therefore they maintain radial files in the conducting phloem.

Parenchyma strands consist of 5 to 8 cells. They usually contain large numbers of small crystals in their lumina (fig. 13-34 upper right).

Fibers are 20 x 30 µm in diameter and have lignified thick secondary walls. They average 1.00 to 1.17 mm in length (tables 13-1 through 13-3). Some of them are twisted or branched (fig. 13-34 bottom right). It could not be confirmed whether they are phloem fibers or fiber-sclereids; that is, whether they mature in the conducting phloem or in the nonconducting phloem. However, some of them appear to be developed from the members of parenchyma strands (fig. 13-34 top right). Consequently, they are called "fibers" here. According to McGrath (1966), the fibers of *Fraxinus velutina* Lindl. mature in the second season after their initiation.

Sclereids develop from the members of parenchyma strands and ray cells.

Phloem rays are homogeneous and of two types, uniseriate and biseriate. The uniseriate rays are about 4 to 9 cells in height. The biseriate rays have uniseriate wings extended at both ends (figs. 13-32 and 13-34 bottom left). Most ray cells and parenchyma strands contain large numbers of small crystals (fig. 13-27 bottom left). Some of the phloem rays are dilated slightly near the periderm.

Periderm is comosed of one to two layers of phelloderm, a layer of phellogen, and three to five layers of phellem. Phellem cells are thin walled and expanded radially in the outer layers. Periderms are formed quite parallel with each other and secondary phloem tissue is sandwiched between them (fig. 13-33). Periderms appear to be formed quite frequently.

Elm, American.—Bark of the trunk at breast height (10 to 15 cm tree diameter) is 2 to 5 mm thick, when dry. The inner bark is 2 to 3 mm thick. The outer bark is rather thin (fig. 13-35) and has shallow fissures. Accumulated scales number only 0 to 2 (0 to 3 mm in thickness). Its color is light brown to grayish brown (fig. 13-1 bottom left).

In the secondary phloem elements are differentiated repeatedly in the following sequence: tangential bands of sieve elements, phloem fibers and crystal-containing parenchyma groups, and a layer of parenchyna strands which contain tanniferous substance (fig. 13-36 top left). In the nonconducting phloem sieve elements are collapsed.

Sieve elements are expanded greatly in the conducting phloem (fig. 13-36 top left). End walls of sieve elements are variable from nearly horizontal to oblique with simple sieve plates (fig. 13-36 top right). Sieve areas on the side wall are horizontally long-oval or oblong and aligned in a vertical row. The cell walls of sieve elements have very thin nacreous thickening (fig. 13-36 top left). Esau and Cheadle (1958) did not discern nacreous walls in *Ulmus*.

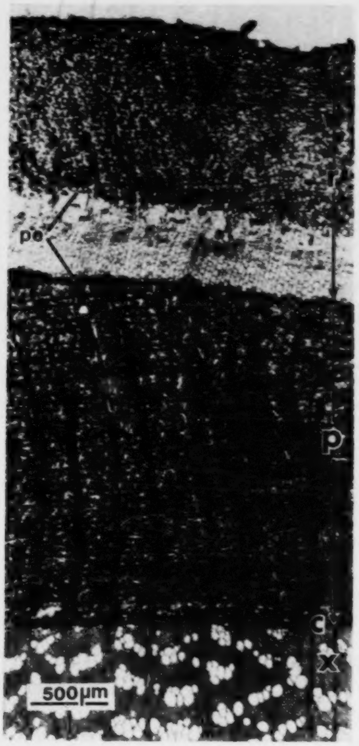

Figure 13-35.—American elm transverse section of entire bark; p, secondary phloem; r, rhytidome; pe, periderm; c, cambium; x, xylem. (Photo from Nanko and Côté 1980.)

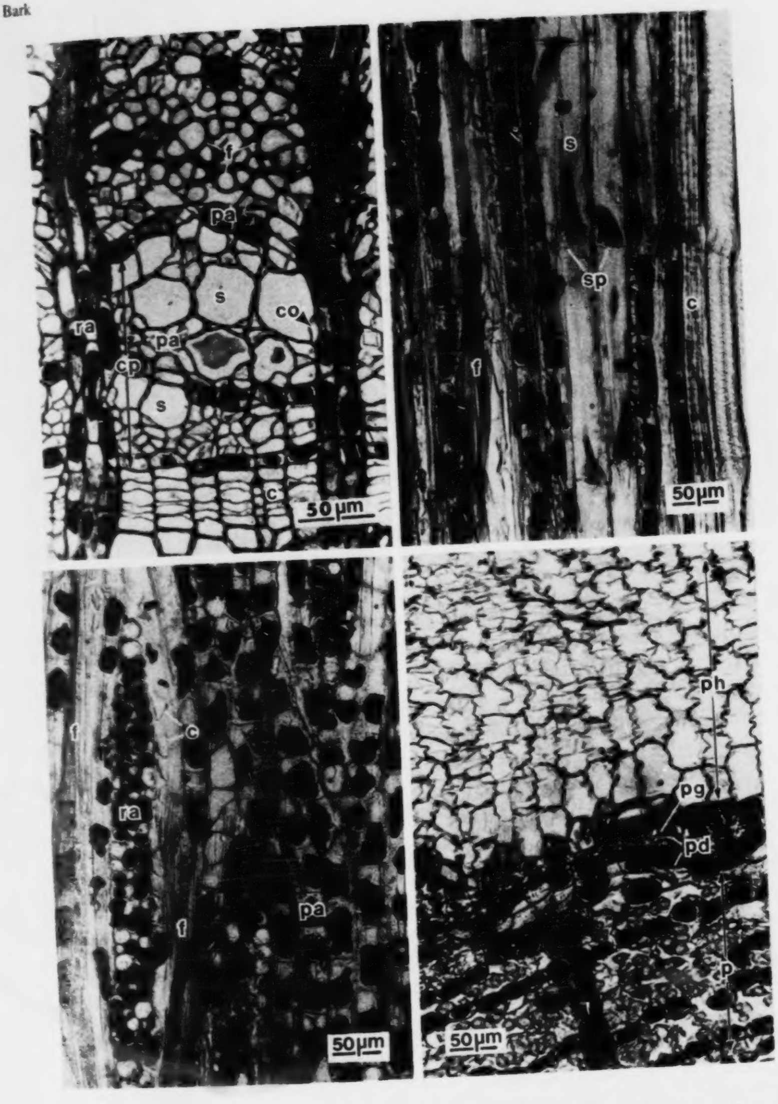
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Figure 13-36.—American elm. (Top left) Transverse section of (cp) conducting and nonconducting phloem. (Top right) Radial section of secondary phloem. (Bottom left) Tangential section of nonconducting phloem. (Bottom right) Transverse section of the periderm. Symbols: c, cambium; co, companion cell; f, fiber; p, secondary phloem; pa, phloem parenchyma; pd, phelloderm; pg, phellogen; ph, phellem; ra, ray; s, sieve element, sp, sieve plate. (Photos from Nanko and Côté 1980.)

Phloem parenchyma cells are of two types (fig. 13-36 top left). One is parenchyma strands which contain tanniferous substance. These are aligned in tangential bands and consist of 4 to 5 parenchyma cells. The other type of parenchyma are short cells, sporadically distributed with fibers, each containing a monohydrate calcium oxalate crystal of twin crystal type (Frey-Wyssling and Blank 1938). Crystals are quite abundant in the secondary phloem.

Phloem fibers are 11 to 15 x 17 μm in diameter with narrow lumens (fig. 13-36 top left), and average about 1.07 mm in length (tables 13-1 through 13-3). The secondary walls consist of outer lignified wall and inner gelatinous wall. Sclereids do not develop on the secondary phloem.

Phloem rays are 1-4 (mostly 2-3)-seriate, essentially homogeneous and are not dilated in the outer part of the secondary phloem (fig. 13-36 top left and bottom left). Cells are mainly procumbent and contain tanniferous substance. Some of them contain twin crystals of calcium oxalate.

Periderm is composed of two to three layers of phelloderm, a layer of phellogen, and thick phellem (fig. 13-36 bottom right). Phelloderm, phellogen, and some phellem cells near the phellogen contain tanniferous substances. Phellem cells are thin walled. They are radially elongated in the outer part of the phellem but collapsed.

Elm, winged.—The structure of winged elm bark is very similar to that of American elm except that: (1) inner bark of winged elm is a little thinner, but the outer bark is much thicker than that of American elm (fig. 13-37); (2) phellem is thicker than that of American elm (fig. 13-37); and (3) sclereids and crystal-containing sclerified cells are differentiated from parenchyma strands in the nonconducting phloem (fig. 13-38). Calcium-oxalate crystals contained in the sclerified cells are of the twin crystal type.

Bark of the trunk at breast height (10 to 15 cm tree diameter) usually is 5 to 10 mm in thickness when dry. The inner bark is 2 mm thick, and the outer bark varies from 2 to 8 mm according to the persistency of its scales. The number of overlapped scales is 1 to 5. Outer bark often shows deep longitudinal fissures divided by interlacing flat ridges (fig. 13-1 bottom right). Brownish yellow colored cork tissue, which is very soft, is freqently exposed.

The minute anatomy of winged elm is similar to that of American elm (fig. 13-36). Phloem fiber diameter (9 to 15 x 17 μm) and length (.83 to 1.10 mm) are not much different than in American elm (tables 13-1 through 13-3).

Hackberry.—Bark of hackberry is brownish gray, rather smooth (fig. 13-2 top left), and comparatively thin (1 to 2.5 mm, mostly 1.5 to 2 mm) at breast height (10 to 15 cm tree diameter). It consists mostly of the secondary phloem and is characterized by the development of corky warts or longitudinally long ridges in limited areas.

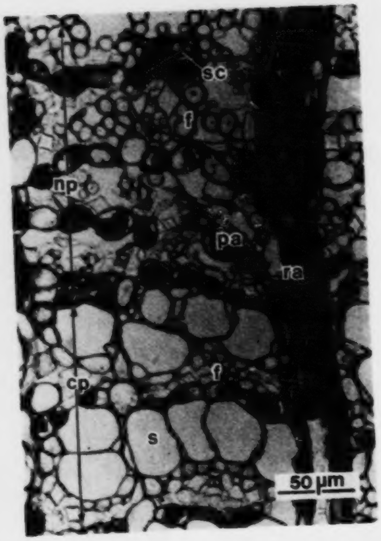

Figure 13-38.—Transverse section of (cp) conducting and (np) nonconducting phloem in winged elm; f, fiber; pa, phloem parenchyma; ra, ray; s, sieve element; sc, sclereid. (Photo from Nanko and Côté 1980.)

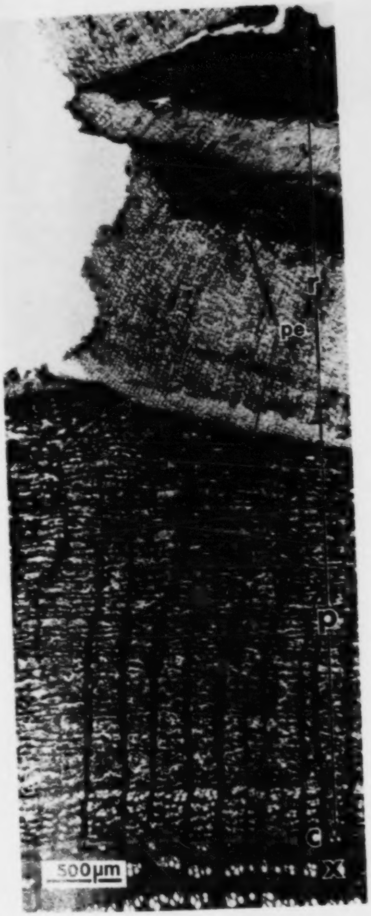

Figure 13-37.—Winged elm. Transverse section of entire bark; p, secondary phloem; r, rhytidome; pe, periderm; c, cambium; x, xylem. (Photo from Nanko and Côté 1980.)

In the conducting secondary phloem sieve elements tend to be arranged in tangential bands, 1 to 3 cells thick with some parenchyma strands dispersed within the band (figs. 13-39 and 13-40 left). Parenchyma strands also form tangential bands, 2 to 4 cells thick, and they are arranged alternately with the sieve elements/parenchyma strand groups. Phloem fibers appear sporadically or in small groups in the tangential bands of parenchyma strands (fig. 13-40). In the non-conducting phloem sieve elements are collapsed completely, and large groups of sclereids develop (fig. 13-39). Sclereid groups form several tangentially aligned broad bands.

r
sc
sc
p
sc
ra
c
100µm
x

Figure 13-39.—Hackberry. Transverse section of (p) secondary phloem and (r) rhytidome cut in the region of corky warts; c, cambium; ra, ray; sc, sclereid; x, xylem. (Photo from Nanko and Côté 1980.)

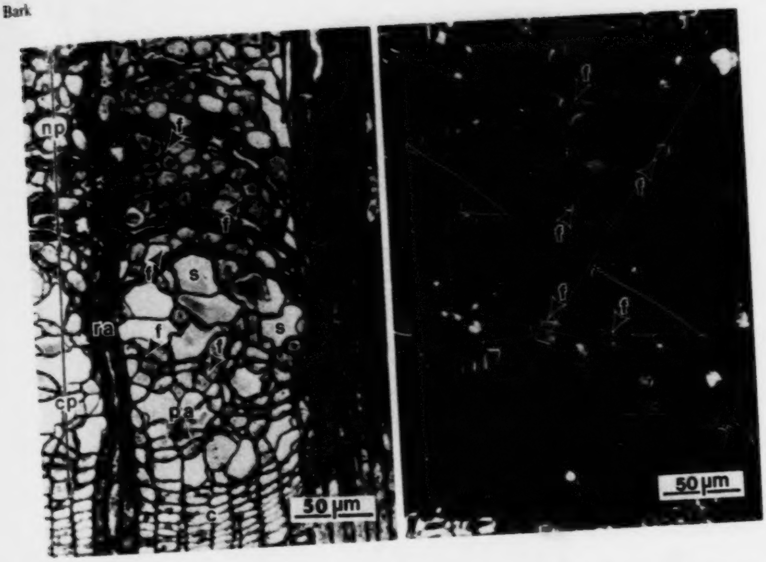

Figure 13-40.—Hackberry. (Left) Transverse section of (cp) conducting and (np) nonconducting phloem. (Right) Same, but photographed under polarized light to show location of (f) phloem fibers. Symbols: pa, phloem parenchyma; ra, ray; s, sieve element. (Photo from Nanko and Côté 1980.)

Sieve elements are expanded greatly in the conducting phloem (fig. 13-40 left). They have almost horizontal to oblique simple sieve plates (fig. 13-41 right). Sieve areas on the lateral walls are not highly specialized in network structure.

Parenchyma strands consist of 4 to 8 (mainly 4 to 5) cells. Some members of the parenchyma strands are occasionally divided into chambers containing a druse crystal in each chamber.

Phloem fibers (13-40) are very difficult to detect without the aid of the polarizing microscope because they are small in diameter (10 µm x 12 µm). They have unlignified cell walls. The cell wall is quite thick, and the lumen is very narrow (fig. 13-23 left); length is 1.32 to 1.99 mm (tables 13-1 through 13-3). Phloem fibers have been seldom reported in the bark of *Celtis* (Holdheide 1951).

Sclereids and crystal-containing sclerified cells—types of stone cells—are differentiated from parenchyma strands and from some ray cells (figs. 13-39 and 13-41 left). They often retain their original shape and size but mostly are expanded. Calcium-oxalate crystals contained in the sclerified cells are of the twin crystal type.

Phloem rays are heterogeneous and 5-8 (mostly 7-8)-seriate (fig. 13-41 right). Marginal ray parenchyma cells often contain druse crystals.

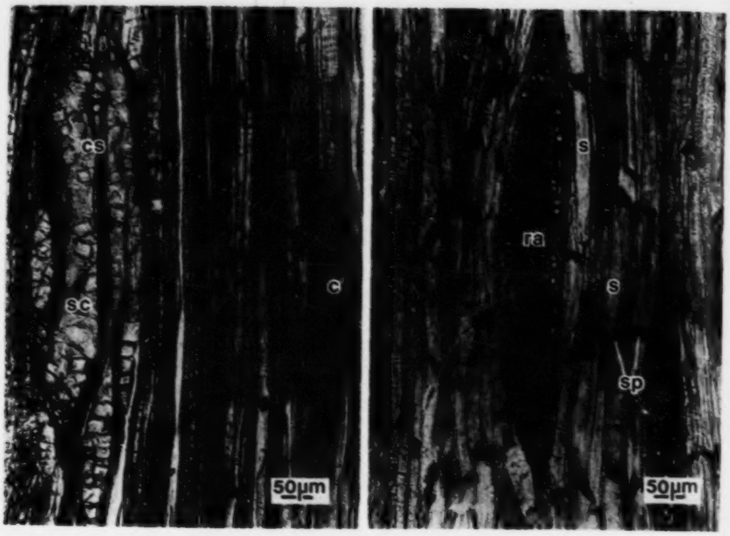

Figure 13-41.—Hackberry. (Left) Radial section of the secondary phloem. (Right) Tangential section of conducting phloem showing broad (ra) rays and (s) sieve elements. Symbols: c, cambium; cs, crystalliferous sclerified cell; sc, sclereid; sp, sieve plate. (Photo from Nanko and Côté 1980.)

In most of the bark, periderm formation is quite limited and persistent. It consists of 1 to 2 layers of phelloderm, a layer of phellogen, and rather thin phellem. The phellem cells are flat and thin walled. In the area of corky warts or ridges, periderm formation appears to occur more frequently (fig. 13-39). Phellem which consists of radially long cork cells forms thick layers. Phelloderm is also thick in this area with 5 to 15 layers of cells. Periderm formation may occur inside of the phelloderm, and the phelloderm cells are transformed into sclereids and crystalliferous sclerified cells in the rhytidome.

Hickory.—Species of *Carya* in the United States, and their varieties and hybrids are often difficult to identify (Harlow et al. 1979). Trees studied to prepare this description were all true hickories, but included several species. External bark characteristics of bitternut, mockernut, pignut, and shagbark hickories are shown in figures 3-37 through 3-40. The color, as well as the texture of mockernut hickory bark is shown in figure 13-2 (top right).

In general, stembark thickness at breast height (10 to 15 cm tree diameter) varies from 6 to 12 mm. Inner bark is rather thick (fig. 13-42), generally 4 to 7 mm thick when dry, but it often becomes very thin at the sites where periderm is formed very deeply in the secondary phloem.

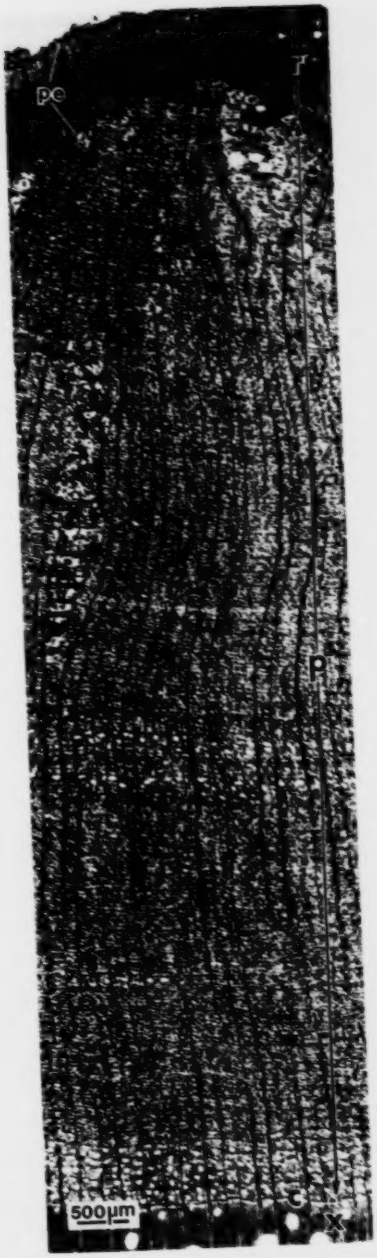

Figure 13-42.—Hickory. Transverse section of entire bark; c, cambium; p, secondary phloem; pe, periderm; r, rhytidome; x, xylem. (Photo from Nanko and Côté 1980.)

In the conducting phloem, parenchyma strands containing tanniferous substance are aligned in tangential bands (fig. 13-43 top left). The spaces between those tangential bands are mostly filled with a great number of phloem fibers. Sieve elements are distributed among the phloem fibers singly or in small groups of 2 to 3 cells (fig. 13-43 top left). They are often attached to the tangential bands of parenchyma strands and are usually surrounded by such strands. Crystal-containing parenchyma strands are often associated with tangential bands of parenchyma strands or distributed sporadically in the groups of phloem fibers (fig. 13-43 top right). In the nonconducting phloem most of the sieve elements are collapsed completely. Some phloem rays are dilated in the outer part of the secondary phloem (fig. 13-42).

Sieve elements are expanded greatly in the conducting phloem (fig. 13-43 top left). They have inclined compound sieve plates (fig. 13-43 bottom left). Sieve areas on the lateral walls are quite characteristic. They are highly specialized and they exhibit a specific scalariform arrangement (fig. 13-43 bottom left). Sieve members have a quite thin nacreous thickening.

Parenchyma strands which are aligned in tangential bands between rays, as viewed on transverse section, consist of 4 to 8 (mainly 6 to 7) cells which frequently contain tanniferous substance (figs. 13-42 and 13-43 top left). Crystal-containing parenchyma strands have styloid crystals in most of the cells (fig. 13-43 top right); the crystals have sheaths on their surfaces (fig. 13-27 bottom right).

Phloem fibers are quite abundant in the secondary phloem. The inner layer of the secondary wall is unlignified, the outer only lightly; the two tend to separate from each other (fig. 13-23 right). They are 10 x 25 μm in diameter and have moderately large lumina. Their length averages about 1.18 mm (tables 13-1 through 13-3).

Sclereids do not develop in the secondary phloem.

Phloem rays are mostly heterogeneous and 1-3 seriate. Uniseriate rays are 10 to 15 cells in height. One- to two-seriate rays have uniseriate wings extended at both ends. Ray cells contain tanniferous substances. Large druse crystals are contained in the dilated portion of the rays.

Periderm is composed of 10 to 30 layers of phelloderm, a layer of phellogen, and very thick phellem (fig. 13-43 bottom right). Phelloderm, phellogen, and several layers of phellem cells near the phelloderm contain tanniferous substance. Cell walls of phellem cells are rather thick.

Maple, red.—The dry bark of the trunk at breast height (10 to 15 cm tree diameter) varies from 2 to 4.5 mm in thickness depending on the degree of rhytidome development. The inner bark is almost constant in thickness (2 to 3 mm). The color of the bark varies from light gray to grayish brown (fig. 13-2 bottom). The bark without rhytidome is smooth. After the development of rhytidome, it is broken into long flat ridges forming shallow fissures.

The secondary phloem (fig. 13-44) may differentiate in the following sequence: sieve elements, phloem fibers, parenchyma strands. Sometimes, probably in poor growing seasons, phloem fibers are not formed (fig. 13-45 top left). In the nonconducting phloem, sieve elements are collapsed, phloem rays are dilated, and sclereids develop.

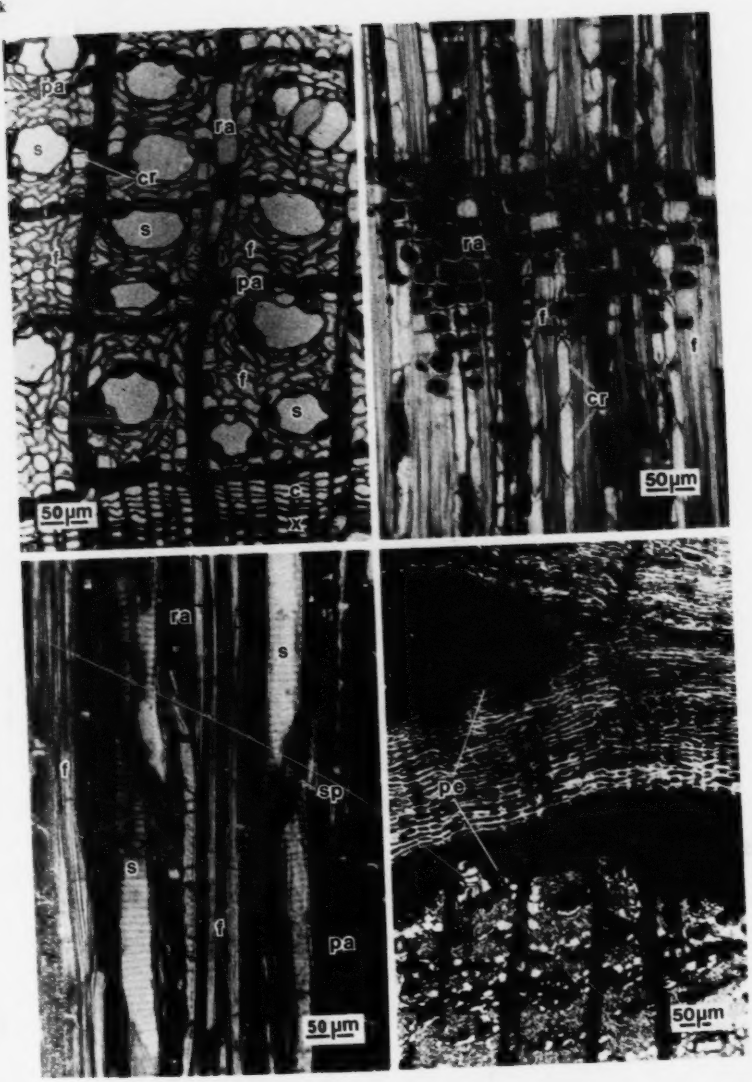
pa
ra
s
cr
s
f
f
pa
f
s
s
c
x
50µm
ra
f
cr
f
50µm
ra
s
f
sp
s
f
pa
50µm
pe
50µm

Figure 13-43.—Hickory. (Top left) Transverse section of the conducting phloem. (Top right) Radial section of the nonconducting phloem showing (cr) crystals. (Bottom left) Tangential section of the conducting phloem showing the scalariform sieve areas of (s) sieve elements. (Bottom right) Transverse section of the (pe) periderm. Symbols: c, cambium; f, fibers; pa, phloem parenchyma; pe, periderm; sp, sieve plate; ra, ray; x, xylem. (Photo from Nanko and Côté 1980.)

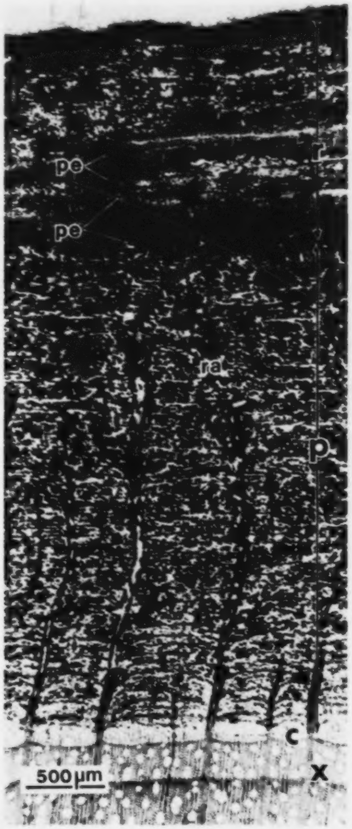

Figure 13-44.—Red maple. Transverse section of entire bark; p, secondary phloem and (r) rhytidome; c, cambium; pe, periderm; ra, ray; x, xylem. (Photo from Nanko and Côté 1980.)

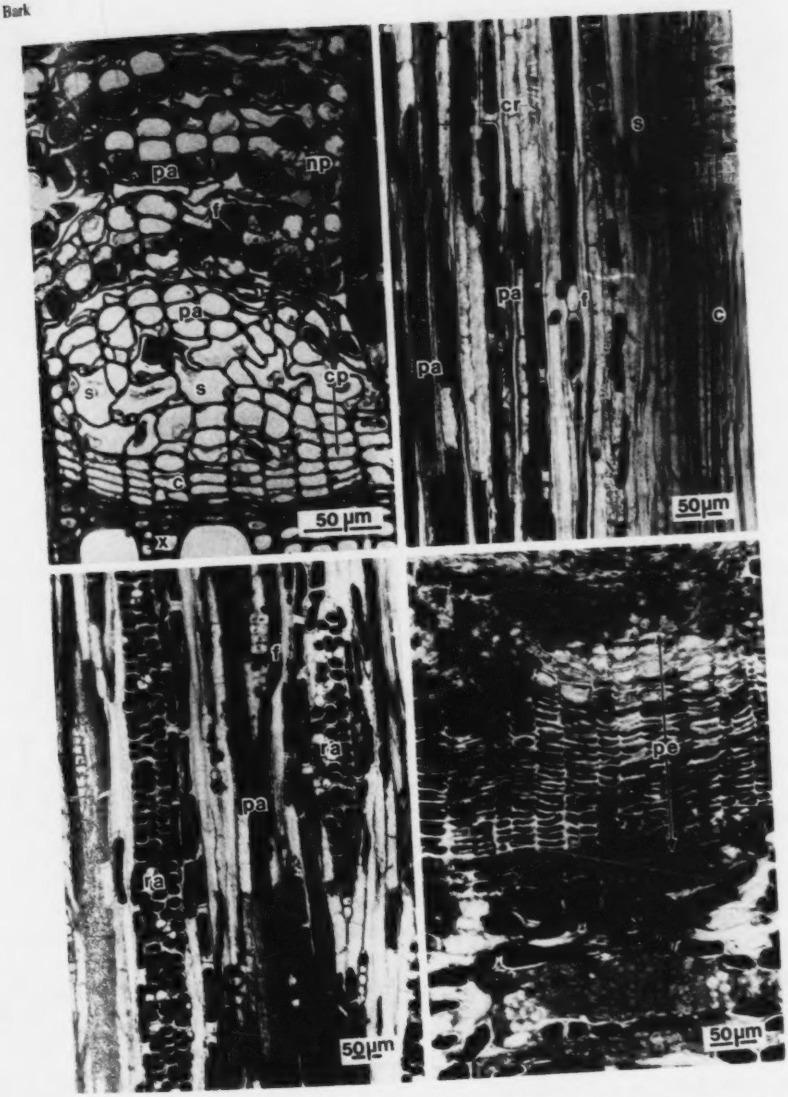
pa
np
f
pa
cp
s
s
c
50 µm
x
cr
s
pa
f
c
pa
50µm
f
ra
pa
ra
50µm
pe
50µm

Figure 13-45.—Red maple. (Top left) Transverse section of (cp) conducting and (np) nonconducting phloem. (Top right) Radial section of secondary phloem. (Bottom left) Tangential section of nonconducting phloem. (Bottom right) Transverse section of the (pe) periderm. Symbols: c, cambium; cr, crystalliferous sclerified cell; f, fiber; pa, phloem parenchyma; ra, ray; s, sieve element; x, xylem. (Photo from Nanko and Côté 1980.)

Sieve elements have nearly horizontal or oblique sieve plates with a single sieve area (fig. 13-45 top right). Sieve areas on the lateral wall exhibit a low degree of specialization with network structure.

Parenchyma strands consist of 3 to 5 long cells. Most of the cells contain tanniferous substance (fig. 13-45). Some cells are divided into compartments and contain a calcium oxalate crystal of twin crystal type in each chamber; other cells contain several crystals without formation of chambers. A few tiny crystals may also be contained in these crystalliferous cells.

Phloem fibers are arranged to form incomplete tangential bands (fig. 13-44). They are about 10 x 15 µm in diameter, and their length averages .64 to .85 mm (tables 13-1 through 13-3). The secondary wall is very thick and lignified, but some phloem fibers have thick gelatinous layers.

Sclereids develop from parenchyma strands and ray cells in the nonconducting phloem. They usually become long and slender by intrusive growth. Many of them are branched.

Phloem rays are homogeneous, 1-3 (mostly 2-3)-seriate and contain tanniferous substance (fig. 13-45 bottom left). Rays become slightly dilated in the outer part of the secondary phloem (fig. 13-44).

Periderm is composed of 2 to 3 layers of phelloderm, a layer of phellogen, and more than 20 layers of phellem (fig. 13-45 bottom right). Phelloderm cells contain tanniferous substance. Phellem cells are thin walled and flat.

Oak, southern red.—The outer surface of the dark brown bark has rough ridges separated by deep fissures (figs. 13-5 top right and 12-44). The thickness of the bark at breast height (9 to 13 cm tree diameter) ranges from 5 to 10 mm. The inner bark is 3 to 5 mm thick, and the outer bark is 2 to 5 mm thick.

The microscopic structure of southern red oak bark (figs. 13-46 and 13-47) is almost the same as that of white oak except for structure of the periderm, which in southern red oak is composed of a single layer of phelloderm, a layer of phellogen, and thick phellem. Phellem cells are usually flat with thin suberized walls.

Phloem fibers have a radial diameter of about 15 µm and average 0.80 to 0.90 mm long (tables 13-1 through 13-3). They have gelatinous layers (fig. 13-25 left).

Oak, white.—White oak has grayish brown to brown bark, scaly on the surface, and shows longitudinal fissures divided by interlacing flat ridges (figs. 13-5 bottom right and 12-43).

Stembark at breast height (9 to 13 cm tree diameter) usually ranges from 4 to 6 mm in thickness in dry condition. Its inner bark (fig. 13-48) is about 2 to 3 mm thick, and the outer bark varies according to the persistency of its scales.

In the secondary phloem sieve elements and parenchyma strands are distributed at random (fig. 13-49 top left). Some parenchyma strands containing tanniferous substance are aligned in tangential bands, as are phloem fibers. In the nonconducting phloem, sieve elements are collapsed and sclereids develop forming short, thick, tangentially extended clusters (fig. 13-48).

Sieve elements are expanded in the conducting phloem. Their end walls are oblique and have compound sieve plates. Sieve areas on the side walls have network structure.

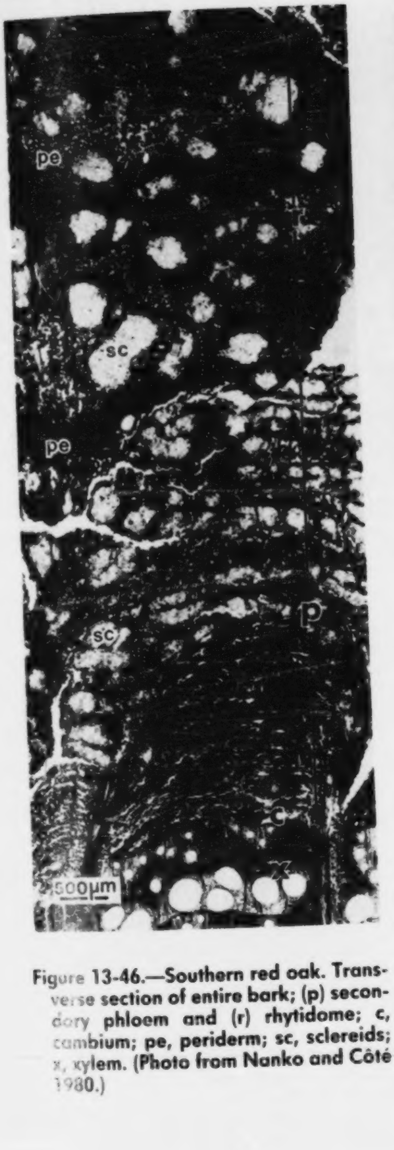

Figure 13-46.—Southern red oak. Transverse section of entire bark; (p) secondary phloem and (r) rhytidome; c, cambium; pe, periderm; sc, sclereids; x, xylem. (Photo from Nanko and Côté 1980.)

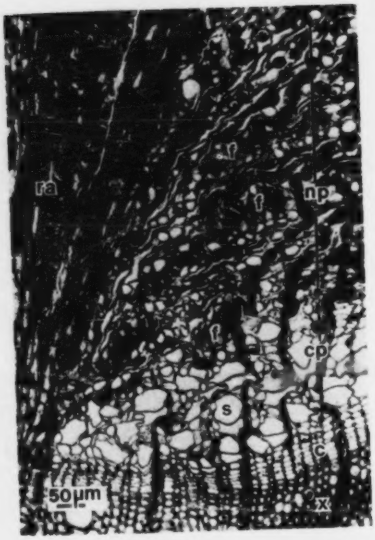

Figure 13-47.—Southern red oak. Transverse section of (cp) conducting and (np) nonconducting phloem; c, cambium; f, fiber; ra, ray; s, sieve element; x, xylem. (Photo from Nanko and Côté 1980.)

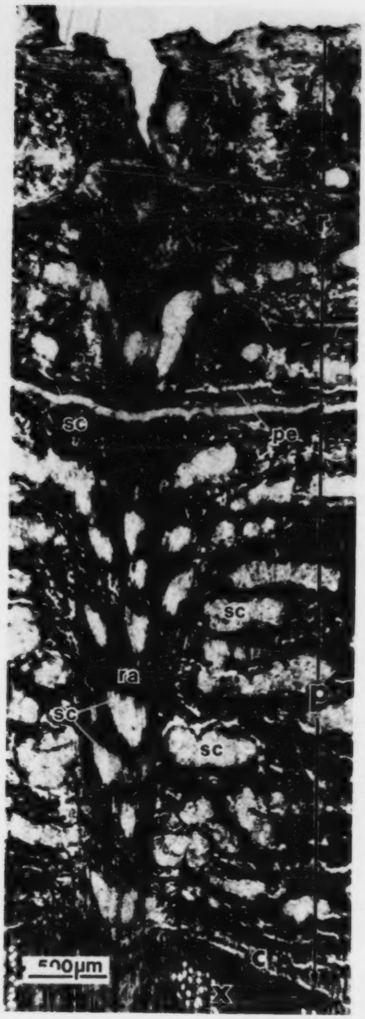
r
sc
pe
sc
ra
sc
sc
p
500µm
c
x

Figure 13-48.—White oak. Transverse section of entire bark, (p) secondary phloem and (r) rhytidome; c, cambium; pe, periderm; ra, ray; sc, sclereid; x, xylem. (Photo from Nanko and Côté 1980.)

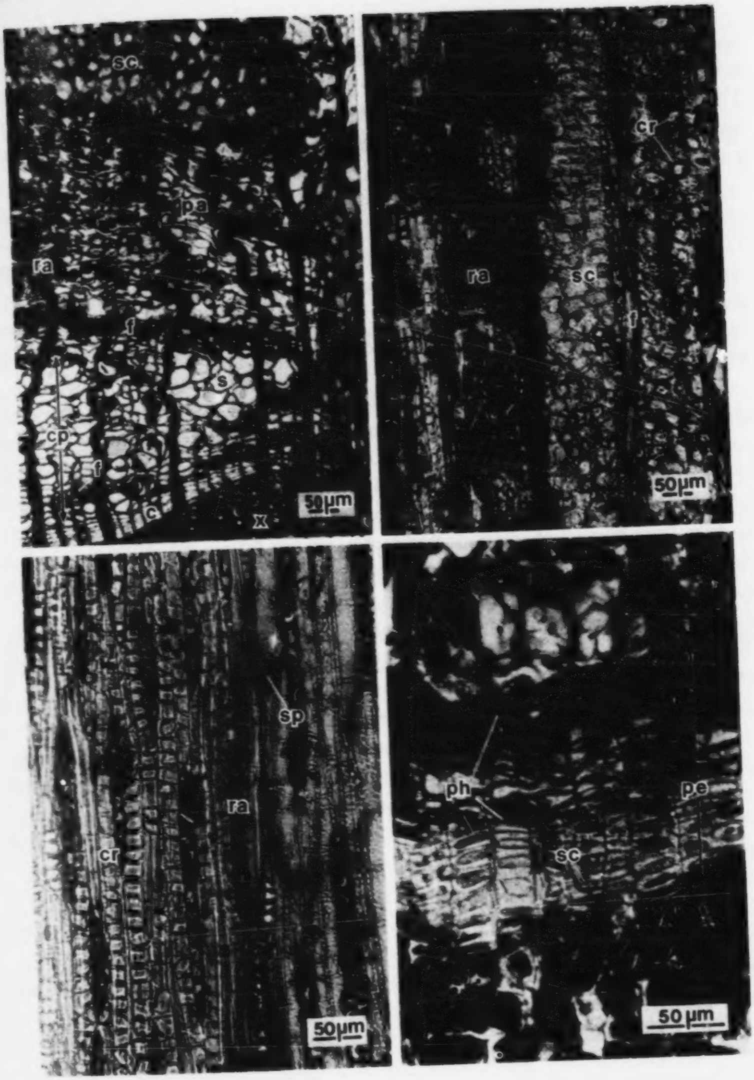
sc
pa
ra
f
s
cp
f
c
x
50µm
cr
ra
sc
f
50µm
sp
ra
cr
50µm
ph
pe
sc
50 µm

Figure 13-49.—White oak. (Top left) Transverse section of (cp) conducting and nonconducting phloem. (Top right) Radial section of nonconducting phloem. (Bottom left) Tangential section of nonconducting phloem showing (cr) chambered crystals. (Bottom right) Transverse section of (pe) periderm showing layer of (sc) sclereids. Symbols: c, cambium; f, fibers; pa, phloem parenchyma; ph, phellem; ra, ray; s, sieve element; sp, sieve plate; x, xylem. (Photo from Nanko and Côté 1980.)

Parenchyma cells are of two types. Those in parenchyma strands differentiating together with sieve elements (fig. 13-49 top left), rarely contain tanniferous substance. The other type are in parenchyma strands aligned in tangential bands. They usually contain tanniferous substance (fig. 13-49 top left); they appear to be terminal (marginal) parenchyma formed at the outer boundary of annual growth increments.

Phloem fibers are 10 x 17 μm in diameter with thick secondary walls and narrow lumina. Their length averages 0.80 to 0.91 mm (tables 13-1 through 13-3). The secondary walls consist mostly of outer lignified wall and inner gelatinous wall, but some have no gelatinous layer (fig. 13-25 right). Phloem fibers are accompanied by chambered crystalliferous cells which contain monohydrate calcium oxalate crystals of twin crystal type (fig. 13-36 top right and bottom left).

Sclereids which form large groups in the nonconducting phloem develop from parenchyma strands and uniseriate ray cells. In both types a major proportion are crystal-containing sclerified cells in mixture with sclereids (fig. 13-49 top left and right). The sclereids which are expanded greatly from original cells are of the stone cell type. Large sclereid groups are also formed in the broad rays (fig. 13-48). They consist of sclereids and many crystalliferous sclerified cells. They generally keep their original shape. Crystals accumulated in the sclerified cells are calcium oxalate of twin crystal type.

Phloem rays are homogeneous and mainly of two sizes, uniseriate and broad (figs. 13-48 and 13-49 bottom left). Ray cells usually contain tanniferous substance and rarely accumulate druse crystals.

Periderm of white oak is distinctive, being composed of one to three layers of phelloderm, several layers of thin-walled, suberized phellem cells, and several layers of sclereids (fig. 13-49 top right). Some periderms lack the layers of sclereids, but most have such layers between phelloderm and phellem, or within the phellem. They appear to be differentiated from phelloderm as suggested by Chang (1954) and Howard (1977). Phelloderm and phellem cells contain tanniferous substance.

It is hypothesized that the phellogen disappears during the dormant season as it differentiates into sclereids or phellem cells.

Sweetbay.—Sweetbay bark is light gray to grayish brown (fig. 13-6 top left). Thickness at breast height in trees 10 to 14 cm dbh is 2.5 to 5 mm. Most sweetbay trees do not have rhytidome (outer bark); on those with rhytidome, only one scale, 1.5 to 2 mm thick, is accumulated (fig. 13-50).

In the secondary phloem tangential bands of sieve elements/parenchyma strand groups, composed mainly of sieve elements, and fiber groups are alternately arranged (figs. 13-50 and 13-51 top left). In the nonconducting phloem sieve elements are somewhat collapsed and sclereids develop. Phloem rays are dilated in the outer part.

Sieve elements are expanded greatly (fig. 13-51 top left) and have very thick nacreous walls ("n" in fig. 13-51 bottom right) in the conducting phloem. The nacreous walls become thin when sieve elements cease functioning. The sieve elements have inclined compound sieve plates which have 4 to 16 (mostly 5 to 9) sieve areas arranged in a scalariform pattern (fig. 13-51 top right and bottom left). Sieve areas on the side walls are mostly oval and arranged in almost vertical rows.

Parenchyma strands contain lipoid substance (fig. 13-51 top left).

Phloem fibers are arranged in nearly radial files (fig. 13-51 top left) indicating minimal intrusive growth. Fibers are rectangular to polygonal in cross section, measuring about 15 x 25 µm in diameter, with very thick lignified secondary walls and nearly occluded lumina (fig. 13-22 left). Average fiber length is in the range from 0.82 to 1.04 mm (tables 13-1 through 13-3).

In the tangential bands of phloem fibers, some thin-walled cells accumulate amorphous glasslike substance in their lumina (fig. 13-30 and 13-51 bottom right). They undergo intrusive growth, are as long as phloem fibers (fig. 13-51 bottom right B), and appear to have quite thin secondary walls. They are considered to be phloem fibers with special functions. Such phloem fibers have been found in *Aphananthe aspera* (Thunb.) Planch (Nanko 1979), *Magnolia obovata* Thunberg, *Magnolia salicifolia* (Sieb. et Zucc.) Maxim (Nanko unpublished data).

Sclereids develop mostly from ray parenchyma and occasionally from axial parenchyma. Sclereids developed from ray parenchyma cells tend to be aligned with the fiber bands. Sclereids also form a few continuous tangential bands in the cortical region (fig. 13-50). Sclereids are mostly expanded and of the stone cell type. Some sclereids accumulate glasslike substance in their lumens as in the case of the phloem fibers. Sclereids do not accompany crystal-containng sclerified cells.

Calcium oxalate crystals are not contained in any elements of the secondary phloem.

Phloem rays are 1-2 (mostly 2)-seriate and essentially heterogeneous. Phloem rays contain oil cells (fig. 13-50 arrows) which develop mostly in the dilated rays.

Periderm is composed of 3 to 6 layers of phelloderm, a layer of phellogen, and very thick phellem. Phellem cells are rectangular to square in cross section, and they tend to be collapsed slightly in the outer part of the phellem.

Sweetgum.—Sweetgum bark is grayish brown, very corky, and has deep furrows (figs. 13-6 top right and 12-42). In trees 11 to 15 cm in dbh, total bark thickness at breast height is 4 to 8 mm. Inner bark is 1 to 2 mm thick and outer bark 2.5 to 10 mm according to degree of periderm formation (fig. 13-52).

In the conducting phloem, sieve elements and parenchyma strands are randomly distributed (fig. 13-53 top left). In the nonconducting phloem fiber-sclereids develop in tangential bands ("f" in fig. 13-53 top left). Sclereids with large rhombic crystals are found in the nonconducting phloem (fig. 13-28).

Sieve elements have inclined compound sieve plates consisting of 3 to 5 sieve areas. Sieve areas on the lateral walls exhibit network structure. The expansion of sieve elements is rather small in the conducting phloem (fig. 13-52). There is some limited collapse of sieve elements in the nonconducting phloem.

pe
sc
p
500 µm
c
x

Figure 13-50.—Sweetbay. Transverse section of entire bark, (p) secondary phloem and rhytidome. Arrows indicate oil cells in phloem rays; c, cambium; pe, periderm; sc, sclereids; x, xylem. (Photo from Nanko and Côté 1980.)

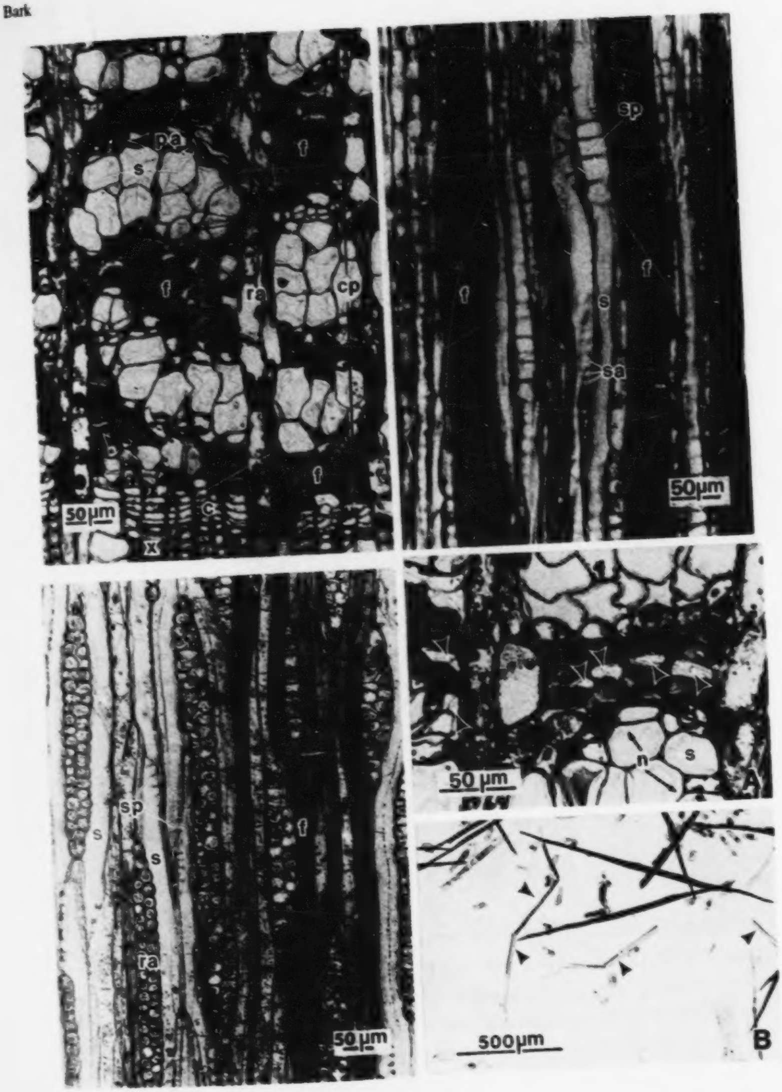

Figure 13-51.—Sweetbay. (Top left) Transverse section of (cp) conducting phloem. (Top right) Radial section of nonconducting phloem. (Bottom left) Tangential section of nonconducting phloem. (Bottom right) Fibers with lumens filled with glasslike substance (arrows). A is a transverse section of tissue including such fibers. B is macerated tissue showing brittle nature of these unstained fibers. Symbols: c, cambium; f, fibers; pa, phloem parenchyma; ra, ray; n, nacreous thickening; s, sieve element; sa, sieve area; sp, sieve plate; x, xylem. (Photo from Nanko and Côté 1980.)

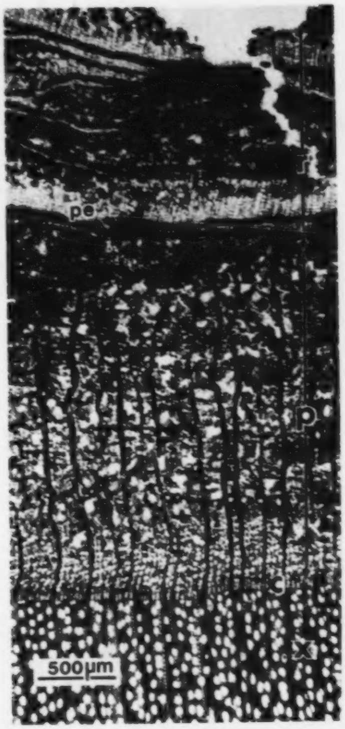

Figure 13-52.—Sweetgum. Transverse section of entire bark, (p) secondary phloem and (r) rhytidome; c, cambium; pe, periderm; x, xylem. (Photo from Nanko and Côté 1980.)

Parenchyma strands contain tanniferous substances. End walls of parenchyma strand cells are mostly inclined. Some parenchyma cells contain very large rhombic crystals (fig. 13-53 top left and right).

Fiber-sclereids have very thick and lignified secondary walls (fig. 13-53 top left). They average 18 to 35 µm in radial diameter and about 45 µm tangentially with very narrow lumina. Fiber length averages .78 to 1.14 mm (tables 13-1 through 13-3).

Crystal-containing sclerified cells develop from axial parenchyma cells in association with fiber-sclereids (fig. 13-53 top left and right). They accumulate large rhombic crystals within the thickened secondary wall. Sclereids also develop from ray cells at intersections with fiber-sclereid bands. They usually retain their original shape and size.

Phloem rays are heterogeneous and of two types, biseriate and uniseriate. Biseriate rays have uniseriate wings extended at both ends. Phloem rays are not dilated. They contain tanniferous substances.

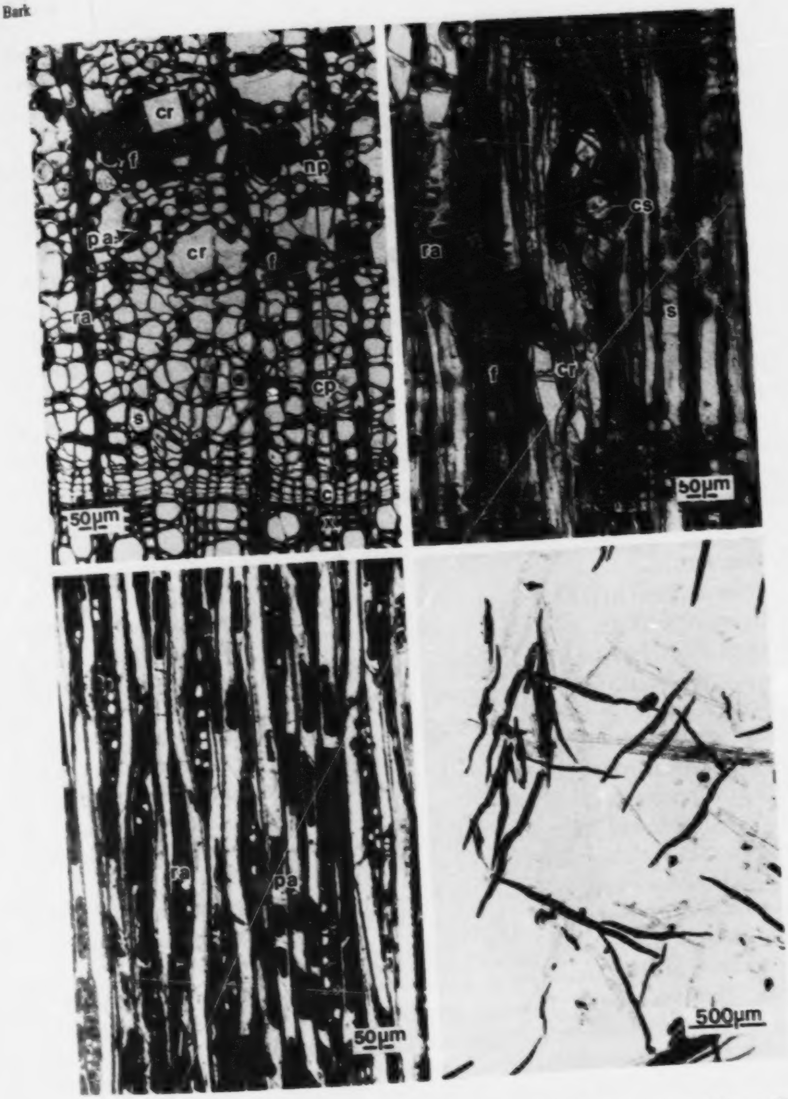
cr
f
np
pa
cr
f
ra
cp
s
c
x
50µm
cs
ra
s
f
cr
50µm
ra
pa
50µm
500µm

Figure 13-53.—Sweetgum. (Top left) Transverse section of (p) secondary phloem. (Top right) Radial section of (np) nonconducting phloem. (Bottom left) Tangential section of nonconducting phloem. (Bottom right) Macerated fiber sclereids. Symbols: c, cambium; cp, conducting phloem; cr, crystal; cs, crystalliferous sclerified cell; f, fiber; pa, phloem parenchyma; ra, ray; s, sieve element; x, xylem. (Photo from Nanko and Côté 1980.)

Periderm consists of 2 to 3 layers of phelloderm, a layer of phellogen, and several layers of phellem. After the formation of the new periderm, phelloderm and parenchymatous cells of the secondary phloem, which are cut off into the rhytidome, expand somewhat and become thick walled.

Tupelo, black.—Bark of black tupelo is brownish gray with flat scaly ridges (fig. 13-6 bottom left) and is generally soft and corky. In trees 10 to 13 cm in dbh, total bark thickness is 3.5 to 6.0 mm, of which 1 to 3 mm is inner bark (fig. 13-54).

In the conducting phloem, sieve elements are solitary or arranged 2 to 3 cells in a radial row (fig. 13-55 top left). Parenchyma strands are distributed in the secondary phloem. Phloem fibers are aligned tangentially (figs. 13-54 and 13-55 top left). Sclereids develop in the nonconducting and sometimes in the conducting phloem. Collapse of sieve elements in the nonconducting phloem is not significant.

Sieve elements have inclined compound sieve plates consisting of 3 to 6 sieve areas (fig. 13-55 top right). Sieve areas on the lateral walls have network structure. The expansion of sieve elements is rather limited in the conducting phloem (fig. 13-55 top left).

Parenchyma strands often contain druse or small rhombic crystals (fig. 13-55 bottom left).

Phloem fibers have very thick and lignified secondary walls (fig. 13-55 top left), are 20 x 25 μm in diameter, and average about 1.15 mm long (tables 13-1 through 13-3). Phloem fibers are always associated with chambered crystalliferous sclerified cells (fig. 13-55 top right).

Sclereids develop from phloem parenchyma and phloem ray cells, and are always associated with crystalliferous sclerified cells. The sclereids developed from ray parenchyma maintain nearly their original size and shape, but those from axial parenchyma are mostly expanded and are a type of stone cell (fig. 13-55 top left). Most of the crystals contained in crystalliferous sclerified cells are large rhombic calcium oxalate crystals.

Phloem rays are heterogeneous and of two types, uniseriate and biseriate. The biseriate rays have uniseriate wings extended at both ends (fig. 13-55 bottom left). Phloem rays are not dilated.

Periderms of black tupelo are as distinctive as those of white oak and yellow-poplar. They are composed of thick phellem, 1 to 2 layers of phelloderm, and 1 to 3 layers of sclereids occurring in bands within the phellem or between the phellem and the phelloderm (fig. 13-55 bottom right). Phellogen was not found in black tupelo periderm. Outer layers of phellem consist of thin-walled and slightly collapsed cells, and the inner layers consist of thick-walled cells. Sclereid cells in the periderms are generally flat in the radial direction (fig. 13-55 bottom right). They appear to be developed from phellogen and some layers of phelloderm after the phellogen ceases to function.

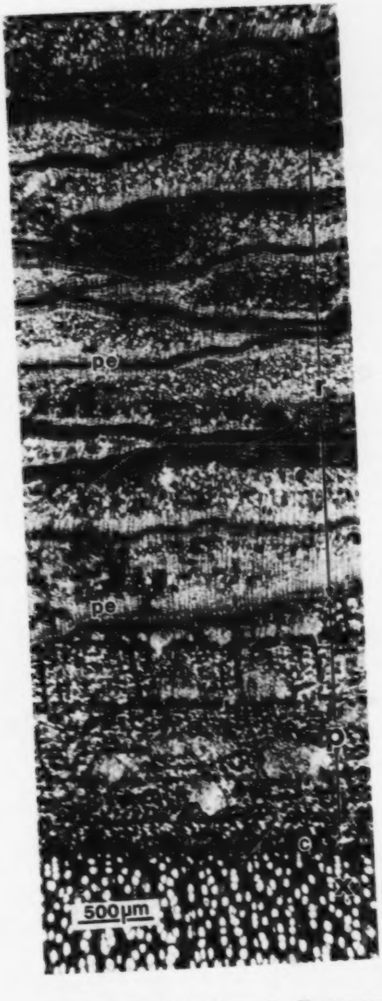

Figure 13-54.—Black tupelo. Transverse section of entire bark including (p) secondary phloem and (r) rhytidome; c, cambium; pe, periderm; x, xylem. (Photo from Nanko and Côté 1980.)

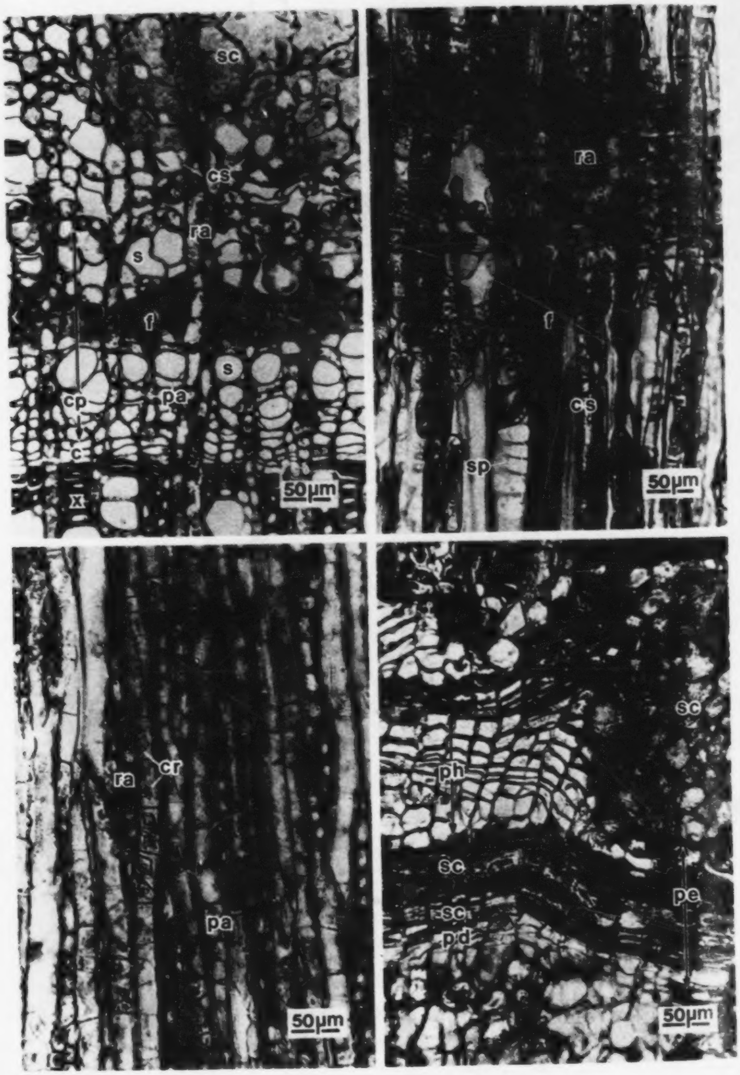
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Figure 13-55.—Black tupelo (Top left) Transverse section of secondary phloem. (Top right) Tangential section of nonconducting phloem. (Bottom left) Radial section of nonconducting phloem. (Bottom right) Transverse section of (pe) periderm showing the layers of (sc) sclereids. Symbols: c, cambium; cp, conducting phloem; cr, crystal; cs, crystalliferous sclerified cell; f, fiber; pa, phloem parenchyma; pd, phelloderm; ph, phellem; ra, ray; s, sieve element; sp, sieve plate; x, xylem. (Photo from Nanko and Côté 1980.)

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Figure 13-56.—Yellow-poplar. Transverse section of entire bark, (p) secondary phloem and (r) rhytidome; c, cambium; pe, periderm; x, xylem. (Photo from Nanko and Côté 1980.)

Yellow-poplar.—Yellow-poplar bark is grayish brown to brown (fig. 13-6 bottom right) and about 2.5 to 7.0 mm thick in dry condition at breast height on trees 12 to 15 cm in dbh. Inner bark at breast height in such trees is 2.5 to 4.0 mm thick. Bark of most trees of this size does not have rhytidome and is very smooth; once rhytidome develops, bark forms shallow furrows longitudinally. The number of overlapped scales is two or three in rhytidome (fig. 13-56).

In the secondary phloem the tangential bands of each phloem element are arranged rather regularly, repeating the following sequence: sieve elements (1 to 2 cells in radial row), parenchyma strands, phloem fibers (1 to 10 cells in radial row), parenchyma strands (fig. 13-57 top left). The thickness of phloem fiber bands is quite variable (fig. 13-56). In the nonconducting phloem sieve elements are collapsed a little, and some of the rays become dilated (fig. 13-56). Sclereids are rarely formed in the inner bark.

Sieve elements in the conducting phloem have very thick nacreous walls, but walls become thin in the nonconducting phloem (fig. 13-57 top left). The end walls of sieve elements are mostly inclined and have compound sieve plates which have 5 to 10 or more sieve areas arranged in a scalariform pattern (fig. 13-57 top right). Sieve areas on the side wall are circular to oval.

Phloem parenchyma cells are in strands which mostly consist of 5 to 7 cells.

Phloem fibers are arranged in nearly radial files (fig. 13-57 top left). They might undergo only a small amount of intrusive growth. In cross section phloem fibers are mostly rectangular, being very narrow radially (8 x 30 μm), or they are somewhat expanded in the radial direction (20 x 25 μm). Cell walls are thick and lignified and lumina are narrow (fig. 13-57 top left). Average fiber length is 1.03 to 1.24 mm (tables 13-1 through 13-3).

Phloem rays are mostly biseriate and heterogeneous (fig. 13-57 bottom left). Oil cells occur in the rays.

The first-formed periderm is composed of 2 to 4 layers of phelloderm, a layer of phellogen, and several layers of phellem. Phellem cells are thin walled and mostly flat in radial direction. All the periderms formed after the first one are distinctive, being composed of 4 to 6 outer layers of thin-walled phellem cells which are square to rectangular in shape, and 4 to 6 inner layers of sclereids which have thick lignified walls and are flat in radial direction (fig. 13-57 bottom right). In both layers cells are arranged regularly, in radial files. Phelloderm and phellogen do not exist. Those structures have been reported in *Liriodendron tulipifera* by de Zeeuw (1939) and Holdheide (1951). They regarded them as stone-cork cells ("sclerified phelloids" according to Esau 1965), which are usually found in the periderm of *Pinus*, (Chang 1954; Howad 1971). But unlike the periderm of *Pinus*, the periderm of *Liriodendron* lacks phellogen and phelloderm. It therefore seems inadvisable to regard the sclereids as belonging to the phellem. They might be phellogen and phelloderm cells which have sclerified after the phellogen stopped functioning. In the secondary phloem tissue being cut off into rhytidome, phloem/parenchyma cells expand, but phloem rays keep nearly their original shape.

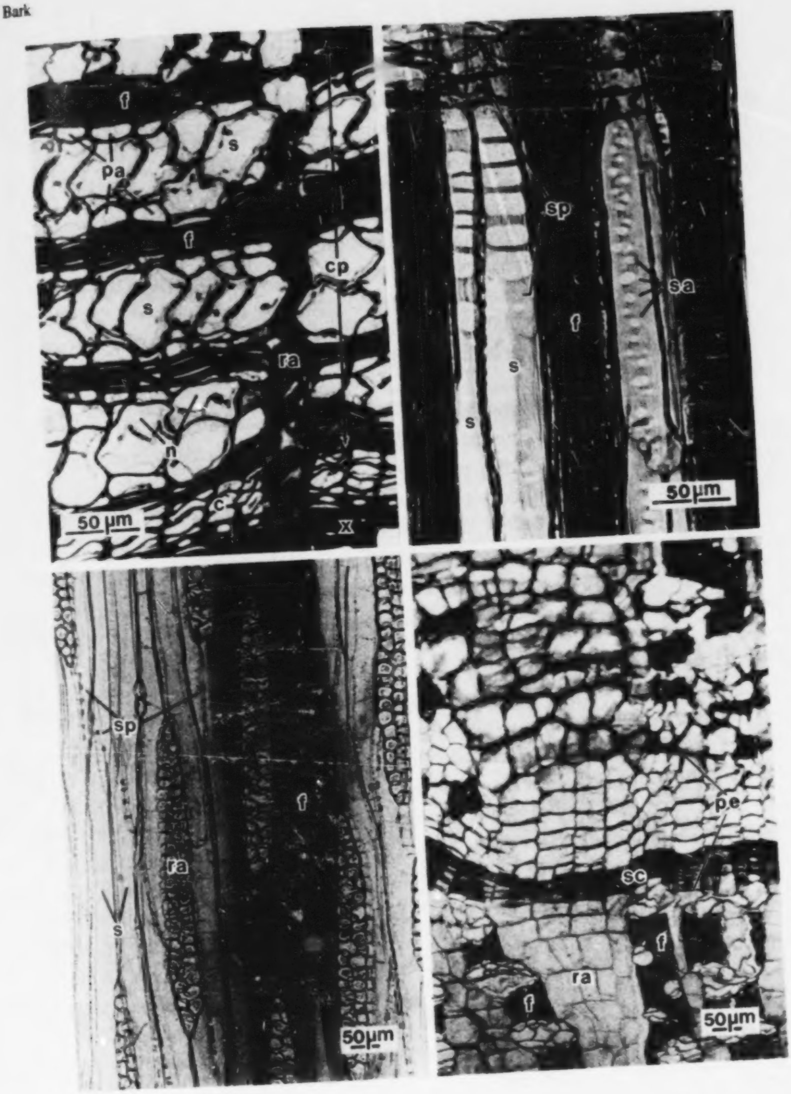
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Figure 13-57.—Yellow-poplar. (Top left) Transverse section of (cp) conducting phloem showing (n) nacreous thickening of sieve elements. (Top right) Radial section of nonconducting phloem showing compound (sp) sieve plates and (sa) sieve area of sieve elements. (Bottom left) Tangential section of nonconducting phloem. (Bottom right) Transverse section of the periderm showing (sc) sclereid layers inside of phellem. Symbols: c, cambium; f, fiber; pa, phloem parenchyma; ra, ray; s, sieve elements; x, xylem. (Photo from Nanko and Côté 1980.)

13-2 THICKNESS

The volume and weight of stembark and branchbark varies among and within hardwood species. Data on the quantities available per acre, tree, log, cord, thousand board feet (Mbf) log scale, and Mbf lumber scale can be found in section 13-3. Proportions of bark in stump-root systems are given in table 14-3.

Because mensurationists assess the content of trees and logs from outside bark measurements, they need estimates of bark thickness in order to compute solid wood volume; the bark thickness of interest to a mensurationist is the distance from a tape stretched outside the bark to the wood surface. A method of accurately measuring this distance from circumferential tape to wood surface—hereafter called **gross bark thickness**—has been described by Mesavage (1969).

Those interested in utilizing bark, measure actual bark thickness at numerous sample points for more accurate assessments of in-place bark volume; usually this is accomplished by scribing eight or more radial lines on log ends or sample disks and measuring the bark thickness outside the vascular cambium at the end of each radial line. This method takes into account the corrugated nature of bark surfaces and the variability in bark thickness around the circumference of a tree; it is hereafter referred to simply as **bark thickness.**

INNER BARK THICKNESS

Inner bark, the light-colored living secondary phloem tissue between vascular cambium and the most recently formed periderm, is the bark portion with greatest potential for chemical utilization. Its thickness is therefore of interest.

C. B. Koch (1971a), in studies of trees sampled in northern West Virginia, found that inner bark thickness was a nearly constant 0.3 inch at heights from 16 to 46 feet in yellow-poplar trees 14 to 16 inches in dbh. In northern red oak of the same dbh, inner bark diminished in thickness from about 0.25 to about 0.15 inch between these heights (fig. 13-58). At stump height, inner bark thickness in yellow-poplar was nearly 0.5 inch and that for northern red oak about 0.35 inch.

Koch found that in yellow-poplar the ratio of inner bark thickness to total bark thickness was about 0.62 at stump height and increased linearly to about 0.80 at a 4-inch top; ratios for northern red oak varied linearly from 0.62 at stump height to 0.90 at 52 feet (4-inch top).

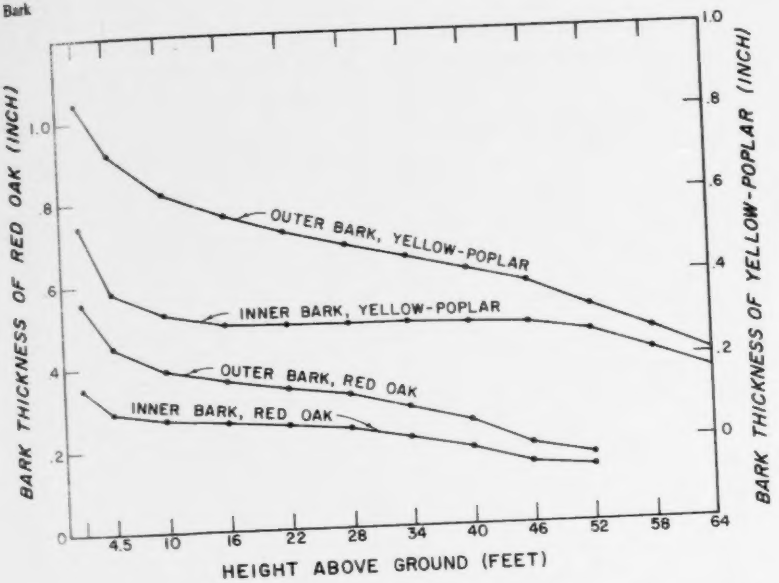

Figure 13-58.—Thickness of inner and outer bark of yellow-poplar and northern red oak trees 14 to 16 inches in dbh, related to height in tree. (Koch 1971a).

Data taken at breast height from ten small (about 15 cm dbh) trees of each of 13 hardwood species sampled among southern pines across the southern ranges of the hardwood species are summarized as follows (Nanko and Côté 1980):

Species	Inner bark thickness
	mm
Ash, green	1.5-2.5
Ash, white	2.0-3.0
Elm, American	2.0-3.0
Elm, winged	2
Hackberry	1.5-2.0
Hickory sp.	4.0-7.0 (with thinner spots)
Maple, red	2.0-3.0
Oak, southern red	3.0-5.0
Oak, white	2.0-3.0
Sweetbay	2.5-5.0
Sweetgum	1.0-2.0
Tupelo, black	1.0-3.0
Yellow-poplar	2.5-4.0

Total bark thickness (inner plus outer bark) of these trees, plus nine additional species of oak, is graphed in figures 13-59 through 13-64.

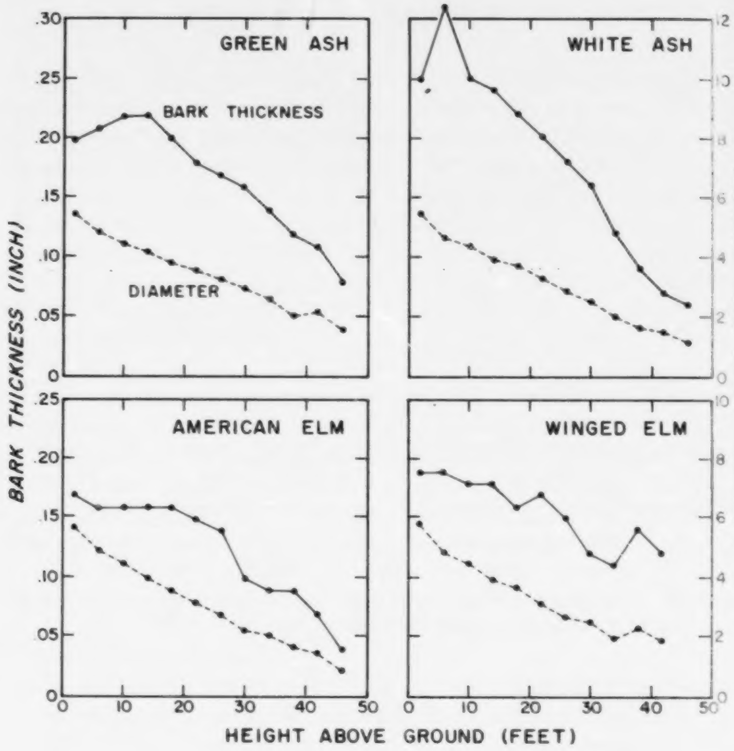

Figure 13-59.—Bark thickness (single) and diameter inside bark of small pine-site green ash, white ash, American elm, and winged elm related to height in stem. Graphs based on 10 trees of each species sampled among southern pines. (Data from Manwiller.[2])

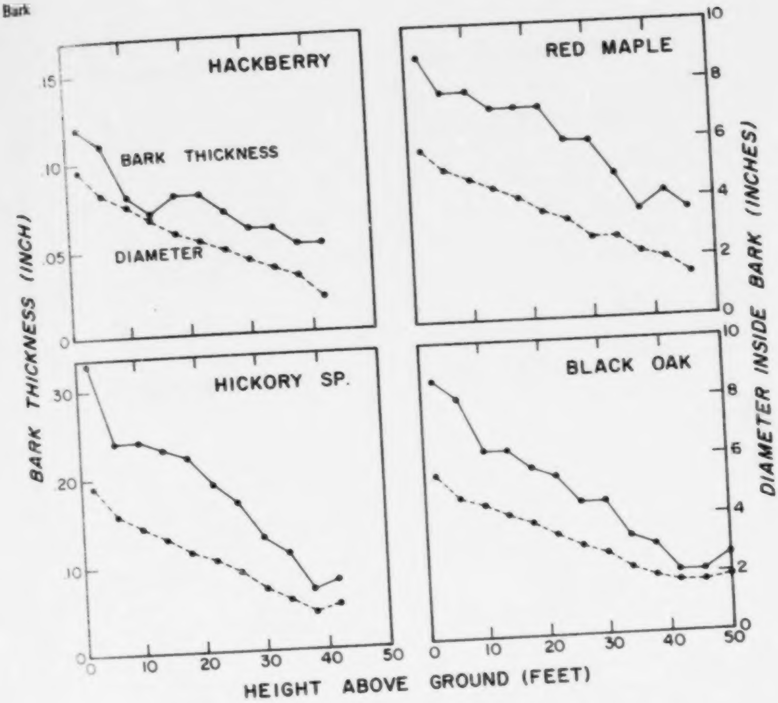

Figure 13-60.—Bark thickness (single) and diameter inside bark of small hackberry, red maple, hickory, and black oak trees related to height in stem. Graphs based on 10 trees of each species sampled among southern pines. (Data from Manwiller.[2])

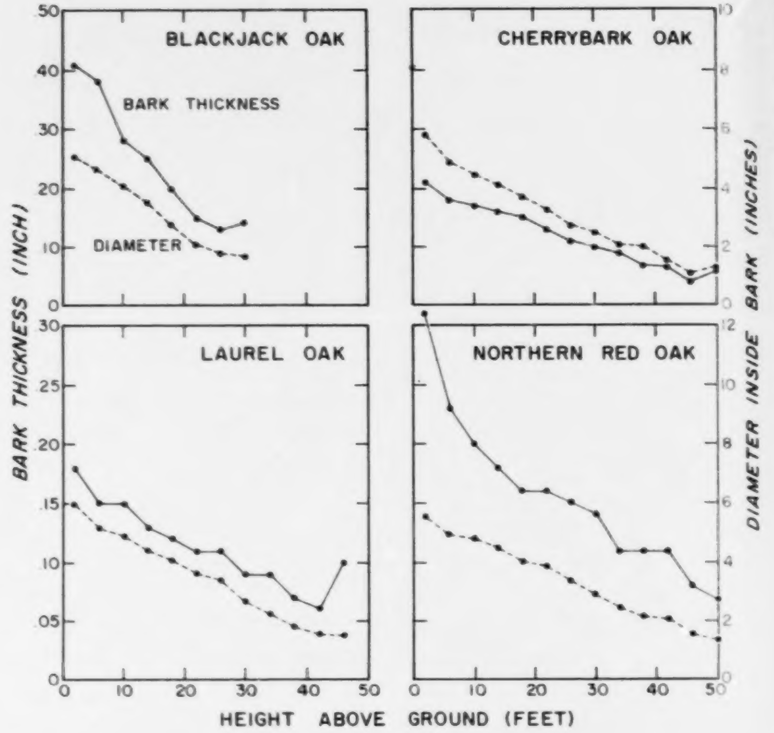

Figure 13-61.—Bark thickness (single) and diameter inside bark of small blackjack, cherrybark, laurel, and northern red oaks related to height in stem. Graphs based on 10 trees of each species sampled among southern pines. (Data from Manwiller.[2])

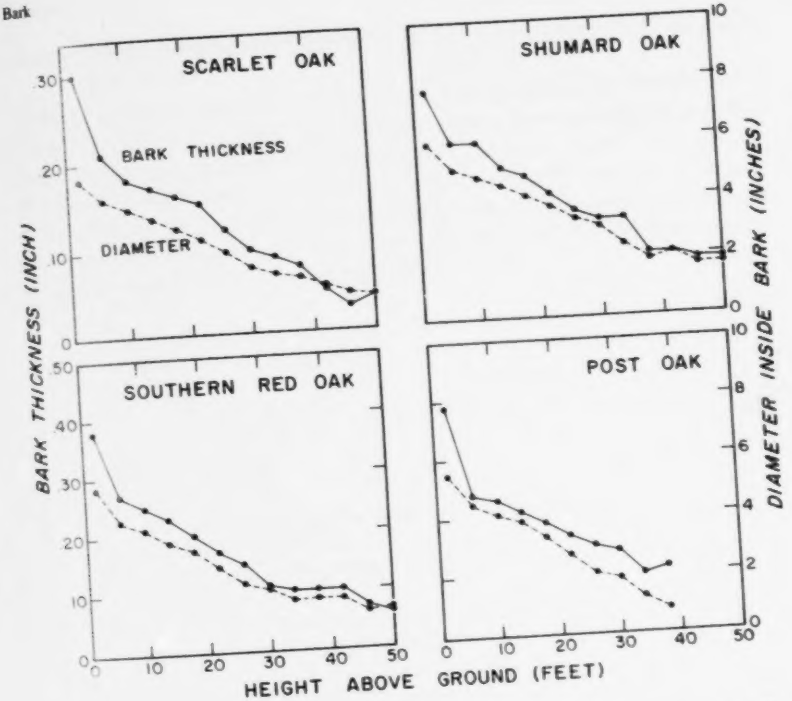

Figure 13-62.—Bark thickness (single) and diameter inside bark of small scarlet, Shumard, southern red, and post oaks related to height in stem. Graphs based on 10 trees of each species sampled among southern pines. (Data from Manwiller.[2])

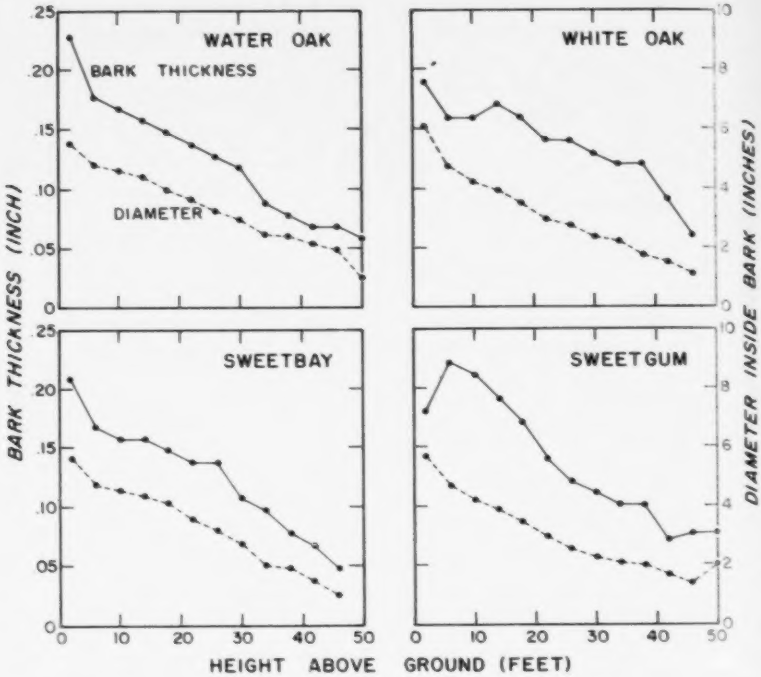

Figure 13-63.—Bark thickness (single) and diameter inside bark of small water oak, white oak, sweetbay, and sweetgum related to height in stem. Graphs based on 10 trees of each species sampled among southern pine trees. (Data from Manwiller.²)

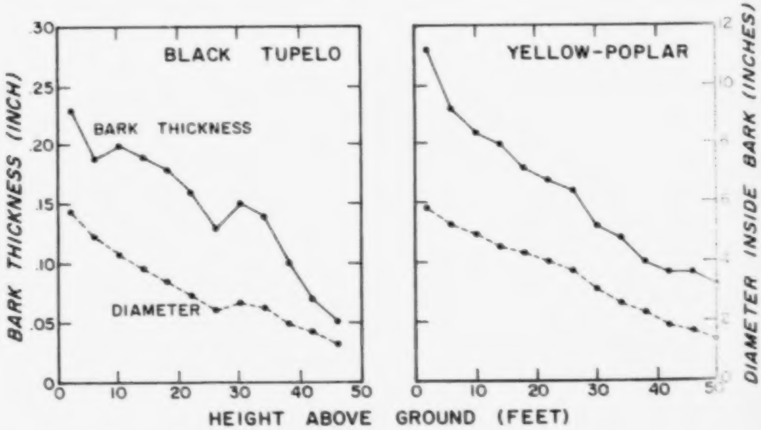

Figure 13-64.—Bark thickness (single) and diameter inside bark of small black tupelo and yellow-poplar trees related to height in stem. Graphs based on 10 trees of each species sampled among southern pines. (Data from Manwiller.²)

PREDICTION OF BARK THICKNESS FROM BREAST-HEIGHT VALUES

The ratio of bark thickness at breast height (4.5 feet) to bark thickness at other heights in a tree stem has been found to either remain constant, increase curvilinearly, or decrease curvilinearly; the relationship varies among species (figs. 13-59 through 13-64). Grosenbaugh (1967) suggested three models for predicting upper-stem diameters inside bark from upper-stem diameters outside bark and observations at breast height; two of these appear applicable to southern hardwoods (Boehmer and Rennie 1976; Wiant and Koch 1974):

$$d = Dk \tag{13-1}$$

$$d = Dk\left[\frac{C_1}{C_2 - \frac{D}{D_1}}\right] \tag{13-2}$$

where:

d = diameter inside bark at height of interest

D = diameter outside bark at height of interest

k = ratio of diameter at breast height inside bark to diameter at breast height outside bark

C_1 and C_2 are constants with the constraint that $C_1 = C_2 - 1.0$; Grosenbaugh (1967) provided values of 9.0 for C_1 and 10.0 for C_2.

D_1 = diameter at breast height outside bark.

Wiant and Koch (1974) found that equation 13-1 proved most accurate for red maple, for yellow-poplar, and for black, scarlet, and northern red oaks sampled near Morgantown, West Virginia.

Space (1973) recommended equation 13-1 for flared or swollen trees, and equation 13-2 for other hardwoods. Boehmer and Rennie (1976), however, concluded that broad recommendations regarding application of one or the other of these equations to hardwoods may reduce accuracy of volume estimates. From a study of sawtimber from a variety of sites 50 miles east of Memphis, Tenn., Boehmer and Rennie found that equations and constants most appropriate for five hardwood species were as follows for trees averaging 8 to 10 inches in dbh outside bark and ranging from 8 to 29 inches:

Species	Most accurate equation	Constant C_2
Oak, cherrybark	13-2	17.05
Oak, southern red	13-1	69.77
Oak, white	13-1	22.62
Sweetgum	13-2	9.89
Yellow-poplar	13-1 or 13-2	19.90

To apply equations 13-1 or 13-2, the ratio k observed at breast height is required. This ratio differs among species and perhaps with geographic location. Values observed by Koch (1971b) in northern West Virginia in 14- to 16-inch trees of five species were as follows:

Species	k
Maple, red	0.960
Oak, black	.916
Oak, northern red	.924
Oak, scarlet	.927
Yellow-poplar	.902

F. G. Manwiller[2] provided data permitting computation of k ratios for 22 species of pine-site hardwoods; his values were measured 6 feet above ground level, rather than at breast height (table 13-4). Ratios at other heights can be obtained from figures 13-59 through 13-64.

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[2] Manwiller, F. G. Unpublished data in *Study File FS-SO-3201-1.59*, U.S. Dept. Agric., For. Serv., South. For. Exp. Stn., Pineville, La.

TABLE 13-4—*Ratio (k) of stem diameter inside bark to stem diameter outside bark at 6-foot height in 6-inch southern hardwoods of 22 species, weight of above-ground foliage-free whole tree and percent stembark and branchbark* (Data from Manwiller[1,2])

Species	Average dbh (outside bark)	k	Whole-tree weight		Stembark[3]		Branchbark[4]	
			Green	Ovendry	Green	Ovendry	Green	Ovendry
	Inches		*Pounds*		*Percent of foliage-free weight above ground*			
Ash, green	5.9	0.914	229.3	151.0	13.8	10.6	3.5	2.4
Ash, white	5.9	.867	209.0	138.4	16.1	13.4	2.9	2.1
Elm, American	5.9	.936	223.5	126.8	12.0	9.4	3.2	2.5
Elm, winged	6.0	.922	238.1	143.0	9.9	8.1	3.6	2.9
Hackberry[5]	6.1	.955	201.0	118.4	9.5	9.2	3.1	2.4
Hickory, sp.	6.0	.900	234.0	150.3	19.5	16.5	3.2	2.6
Maple, red	5.8	.949	240.5	140.2	11.5	10.3	3.8	2.7
Oak, black	6.0	.887	280.0	169.6	17.4	16.1	3.3	2.6
Oak, blackjack	6.0	.835	205.8	125.2	20.1	19.3	4.3	3.8
Oak, cherrybark	6.0	.926	249.1	152.2	13.8	12.8	2.5	1.9
Oak, laurel	6.0	.942	291.1	170.3	11.8	11.5	2.7	2.0
Oak, northern red	6.0	.908	297.9	179.4	16.4	15.4	2.6	2.0
Oak, post	5.9	.893	222.2	137.2	16.1	13.8	4.5	3.9
Oak, scarlet	6.0	.912	258.0	155.8	16.3	14.8	3.0	2.1
Oak, Shumard	5.8	.922	306.7	185.4	14.2	13.3	2.5	1.9

See footnotes on next page.

TABLE 13-4—*Ratio (k) of stem diameter inside bark to stem diameter outside bark at 6-foot height in 6-inch southern hardwoods of 22 species, weight of above-ground foliage-free whole tree and percent stembark and branchbark* (Data from Manwiller[1,2])—Continued

Species	Average dbh (outside bark)	k	Whole-tree weight		Stembark[3]		Branchbark[4]	
			Green	Ovendry	Green	Ovendry	Green	Ovendry
	Inches		----------*Pounds*----------		*Percent of foliage-free weight* --------------------*above ground*--------------------			
Oak, southern red	6.0	.882	232.3	140.6	19.1	17.4	3.3	2.8
Oak, water	5.9	.927	298.1	175.7	14.5	14.0	2.2	1.8
Oak, white	5.9	.933	232.7	144.3	12.0	10.5	2.5	2.1
Sweetbay	5.8	.930	246.6	122.6	13.9	12.0	2.7	2.2
Sweetgum	5.9	.906	208.4	96.8	10.9	12.2	2.5	2.0
Tupelo, black	5.8	.920	202.6	109.0	13.7	12.6	3.0	2.2
Yellow-poplar	6.1	.913	263.3	123.4	16.7	14.1	1.9	1.5

[1] Manwiller, F. G. Unpublished data in Study File FS-SO-3201-1.59, U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Pineville, La.

[2] Based on 10 trees of each species measuring about 6 inches in dbh and sampled among southern pines across the southern ranges of each hardwood species; see table 3-1 for a description of the trees.

[3] The stem was defined as the bole portion above a 6-inch stump height to a stem diameter of 0.5 inch outside bark or to the point of stem division into branches. See table 16-8 for stem top diameter outside bark; it was generally less than 2 inches.

[4] Branches did not include foliage or twigs smaller than 0.5 inch diameter.

[5] Mostly sugarberry.

From data taken in Pennsylvania on cordwood of various diameters cut from throughout tree stems of six hardwoods, Chamberlain and Meyer (1950) reported the following ratios of diameter inside bark to diameter outside bark:

Species	Ratio
Maple, red	0.92-0.94
Oak, black	.86- .88
Oak, chestnut	.84- .88
Oak, northern red and scarlet	.88- .92
Oak, white	.87- .93

Readers interested in further evaluations of the ratio k for use in equations 13-1 or 13-2 can derive them from tabular data in Schnur (1937).

Koch (1971b) found that in northern red oak the ratio of bark thickness to diameter outside bark was essentially constant at 0.032 regardless of height in stem. For yellow-poplar 12 to 14 inches in dbh this ratio was maxium at breast height (0.049), decreased to 0.042 at 16 feet, and was essentially constant above this height. (These values for yellow-poplar can be computed from the ratios graphed in figure 13-65 top.)

ADDITIONAL DATA ON BARK THICKNESS

Published data on bark thickness of southern hardwoods are not plentiful, but are summarized in the following paragraphs arranged alphabetically by species common name.

Ash, green.—See figure 13-59 top left and table 13-4 for data on 6-inch pine-site trees.

Ash, white.—See figure 13-59 top right and table 13-4 for data on 6-inch pine-site trees. Single bark thickness at the top end of 68 16-foot-long white ash butt logs sampled in New York State averaged 0.568 inch (Nyland 1971).

Elm, American and winged.—See figure 13-59 and table 13-4 for data on 6-inch pine-site trees.

Hackberry.—See figure 13-60 top left and table 13-4 for data on 6-inch trees sampled in the South.

Hickory sp.—See figure 13-60 bottom left and table 13-4 for data on 6-inch pine-site trees. Of the important hickories found among southern pines, shagbark hickory probably has the thickest park. In New York, Caldwell (1953) found that shagbark hickory usually has bark less than ¾-inch in thickness, but it is occasionally 1 inch thick.

Maple, red.—See figure 13-60 top right and table 13-4 for data on 6-inch pine-site trees. Single bark thickness at the top end of 68 16-foot red maple butt logs sampled in New York State averaged 0.347 inch. Chamberlain and Meyer (1950) found that in red maple pulpwood the ratio of diameter inside bark to outside bark was 0.92 to 0.94.

Koch (1971b) sampled five red maples in each of three dbh classes (4-6, 8-10, and 12-14 inches) in northern West Virginia, and found that at all heights the ratio of diameter inside bark to diameter outside averaged 0.958; at breast height the ratio was 0.960. There was very little variation in this ratio with tree diameter class and height in tree (fig. 13-65).

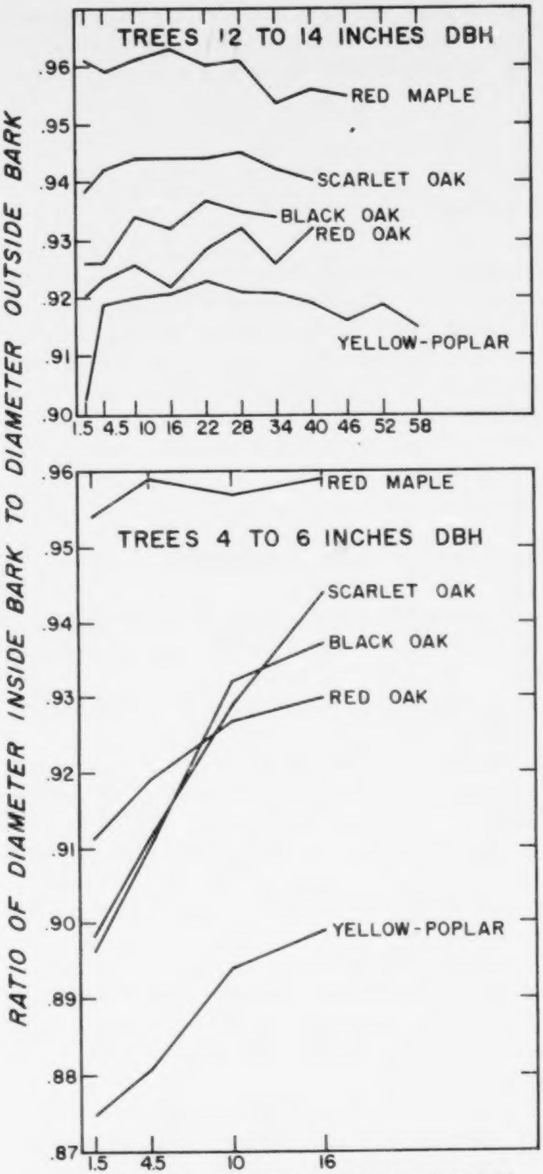

Figure 13-65.—Ratio of diameter inside bark to diameter outside bark related to height above ground in two diameter classes of five species of West Virginia hardwoods. (Drawing after Koch 1971b.)

Oak, black.—See figure 13-60 bottom right and table 13-4 for data on 6-inch pine-site trees. Koch (1971b) sampled five black oaks in each of three diameter classes (4-6, 8-10, and 12-14 inches) in northern West Virginia, and found that at over all heights the ratio of diameter inside bark to outside bark averaged 0.927; at breast height it averaged 0.916. Variation in the ratio was greater in small than in large trees (fig. 13-65).

Oaks, blackjack, cherrybark, and laurel.—See figure 13-61 and table 13-4 for data on 6-inch pine-site trees.

Oak, northern red.—See figure 13-61 bottom right and table 13-4 for data on 6-inch pine-site trees. Single bark thickness at the top end of 121 16-foot red oak sp. butt logs sampled in New York averaged 0.491 inch (Nyland 1971). Chamberlain and Meyer (1950) found that in northern red oak and scarlet oak pulpwood, the ratio of diameter inside bark to outside bark was 0.88 to 0.92.

Koch (1971b) sampled 10 northern red oaks in each of three dbh classes (4-6, 8-10, and 12-14 inches) at each of two locations in northern West Virginia, and found that averaged over all trees and heights in trees, the ratio of diameter inside bark to diameter outside bark was 0.929; at breast height the ratio was 0.924. The ratio increased slightly with increased height in trees of small and large diameter (fig. 13-65).

Oak, scarlet.—See figure 13-62 top left and table 13-4 for data on 6-inch pine-site trees. Chamberlain and Meyer (1950) found that in scarlet oak pulpwood the ratio of diameter inside bark to outside bark was 0.88 to 0.92.

Koch (1971b) sampled five scarlet oaks in each of three dbh classes (4.6, 8-10, and 12-14 inches) in northern West Virginia and found that averaged over all trees and heights in trees, the ratio of diameter inside bark to outside bark was 0.934; at breast height the ratio was 0.927. In small trees the ratio increased with height in tree, but in larger trees was nearly constant (fig. 13-65).

Oaks, Shumard, southern red, and post.—See figure 13-62 and table 13-4 for data on 6-inch pine-site trees.

Oak, water.—See figure 13-63 top left and table 13-4 for data on 6-inch pine-site trees.

Oak, white.—See figure 13-63 top right and table 13-4 for data on 6-inch pine-site trees. Single bark thickness at the top end of 41 16-foot white oak butt logs sampled in New York averaged 0.720 inch (Nyland 1971). Chamberlain and Meyer (1950) found that in white oak pulpwood the ratio of diameter inside bark to outside bark was 0.87 to 0.93.

Sweetbay and sweetgum.—See figure 13-63 bottom and table 13-4 for data on 6-inch pine-site trees. On larger sweetbay trees, bark may be ½- to ¾-inch thick (Maisenhelder 1970).

Tupelo, black.—See figure 13-64 left and table 13-4 for data on 6-inch pine-site trees.

Yellow-poplar.—See fig. 13-64 right and table 13-4 for data on 6-inch pine-site trees. Kellison (1967) sampled at breast height 30- to 50-year-old yellow-poplar trees from 27 stands in North Carolina and found no significant differences in bark thickness among any of the stands.

Koch (1971b) sampled 10 yellow-poplars in each of three diameter classes (4-6, 8-10, and 12-14 inches) at each of two locations in northern West Virginia, and found that averaged over all trees and heights in trees, the ratio of diameter inside bark to diameter outside bark was 0.912; at breast height the ratio was 0.902. In small trees the ratio increased with height above ground, but in larger trees was nearly constant above breast height (fig. 13-65).

13-3 BARK VOLUME AND WEIGHT

In planning for utilization of hardwood bark it is useful to know something of the quantities available per acre, tree, log, cord, and Mbf of logs and lumber.

BARK VOLUME AND WEIGHT PER ACRE

Wiant and Castaneda (1978) prepared yield data per acre based on Schnur's (1937) stand tables for fully stocked, evenaged, second-growth, upland oak forests and weight equations developed by Wiant et al. (1977). In Wiant and Castaneda's tables, which they concluded should be useful in many evenaged, eastern upland oak forests, all stem material less than 4 inches in diameter outside bark, and all limbs were considered branches. Stumps to ½-foot height, roots, and leaves were excluded.

In trees of all diameters 0.25-inch and larger, whole-tree bark above a 6-inch stump height (ovendry weight basis) varied from 2,612 pounds/acre for a 10-year-old site-40 stand to nearly 10 times that much (24,191 pounds/acre) on a 100-year-old site-80 stand (table 13-5). Branchbark comprises about one-third the weight of above-ground whole-tree bark weight (table 13-6). Weight of stembark is given in table 13-7. Percentage of whole-tree, above-ground weight per acre represented by bark decreases with increasing site index and stand age (table 13-8), varying from 17.9 percent in young stands on poor sites to 13.3 percent in old stands on good sites. **Site index** values of 40 to 80 used in tables 13-5 through 13-8 refer to height growth attained by dominant and codominant oaks in 50 years.

TABLE 13-5—*Weight of above-ground whole-tree bark (ovendry-weight basis) per acre on trees of two size classes in fully stocked, evenaged, second-growth upland oak forests at ten ages on five sites* (Wiant and Castaneda 1978)

Stand age (years)	Site index 40	50	60	70	80
	Pounds/acre				
	ON ALL TREES 0.25-INCH DBH AND LARGER				
10	2,612	2,742	3,405	3,658	3,975
20	4,608	5,995	6,556	7,739	9,884
30	7,052	9,033	10,614	12,610	13,622
40	9,109	10,908	12,826	14,661	16,068
50	10,499	12,493	15,669	17,367	19,975
60	12,022	14,264	17,103	19,578	21,065
70	12,791	15,377	18,018	20,065	21,822
80	13,935	17,344	19,026	21,319	22,181
90	15,403	18,041	20,377	22,442	23,196
100	16,227	18,998	21,042	22,976	24,191
	ON TREES 5 INCHES DBH AND LARGER				
10	0	0	0	0	0
20	0	493	995	2,324	5,165
30	1,934	4,408	7,101	10,338	12,262
40	5,407	8,343	11,279	13,820	15,617
50	7,878	10,887	14,860	16,928	19,752
60	10,284	13,335	16,627	19,322	20,932
70	11,592	14,756	17,696	19,918	21,740
80	13,053	16,907	18,800	21,212	22,117
90	14,721	17,684	20,210	22,361	23,143
100	15,687	18,732	20,892	22,912	24,151

TABLE 13-6—*Weight of branchbark (ovendry weight basis) per acre on trees 5 inches in dbh and larger in fully stocked, even-aged, second-growth, upland oak forests at ten ages on five sites* (Wiant and Castaneda 1978)

Stand age (years)	Site index 40	50	60	70	80
	Pounds/acre				
10	0	0	0	0	0
20	0	265	513	1,200	2,296
30	1,017	1,961	2,953	3,965	4,491
40	2,286	3,298	4,162	4,750	5,197
50	3,100	4,041	5,026	5,657	6,641
60	3,852	4,661	5,581	6,503	7,190
70	4,114	5,062	5,988	6,934	7,564
80	4,585	5,706	6,590	7,535	7,789
90	4,974	6,197	7,070	7,959	8,262
100	5,455	6,620	7,356	8,246	8,624

TABLE 13-7—*Weight of stembark (ovendry-weight basis) per acre on trees 5 inches in dbh and larger to a 4-inch top diameter outside bark in fully stocked, evenaged, second-growth upland oak forests at ten ages on five sites* (Wiant and Castenada 1978)[1]

Stand age (years)	Site index 40	50	60	70	80
	Pounds/acre				
10	0	0	0	0	0
20	0	368	746	1,904	3,975
30	1,609	3,397	5,331	7,757	9,318
40	4,061	6,371	8,661	10,538	12,048
50	6,018	8,472	11,333	13,374	15,918
60	8,059	10,452	13,276	15,655	17,335
70	9,019	11,745	14,413	16,852	18,191
80	10,470	13,683	16,142	18,357	18,819
90	11,663	15,063	17,389	19,510	20,164
100	13,083	16,252	17,977	20,499	21,300

[1] Values in tables 13-6 and 13-7 do not sum to equal values in table 13-5 because branchbark values (table 13-6) are based on prediction equations that had poorer fits than those for whole trees.

TABLE 13-8—*Percent of foliage-free, above-ground, whole-tree weight per acre (ovendry-weight basis) which is bark in all trees 0.25-inch dbh and larger in fully stocked, even-aged, second-growth upland oak forests at ten ages on five sites* (Wiant and Castaneda 1978)

Stand age (years)	Site index 40	50	60	70	80
	Percent				
10	17.9	17.9	17.5	17.4	17.4
20	16.6	16.3	16.3	16.2	15.9
30	15.5	15.3	15.4	15.3	15.2
40	15.0	14.9	14.9	14.8	14.6
50	14.7	14.5	14.6	14.3	14.2
60	14.3	14.4	14.1	14.1	14.0
70	14.3	14.2	13.9	13.8	13.8
80	14.2	14.0	13.8	13.5	13.4
90	14.0	13.6	13.7	13.5	13.3
100	13.7	13.5	13.6	13.3	13.2

BARK VOLUME AND WEIGHT PER TREE

Bark volume per tree varies with species, tree size and vigor, geographic location, and tree portion considered. Small hardwoods have a greater percentage of bark than larger hardwoods (table 13-8); Wartluft (1977) found that above-ground portions of Appalachian hardwoods measuring 1 inch in dbh outside bark were about 22 percent bark (green-weight basis), but 8-inch hardwoods had only about 12 percent of their above-ground green weight in bark. Topwood of hardwood sawtimber sampled by Wartluft (1978) in southern West Virginia and Virginia had a high percentage of bark—22 percent for hard hardwoods and 27 percent for soft hardwoods (green-weight basis).

Stump-root systems of 6-inch pine-site hardwoods have average bark content of about 12.6 percent, ovendry basis; of 22 species studied, black tupelo stump-root systems had least bark (6.1 percent) and scarlet oak most (20.5 percent). See table 14-3.

In an Arkansas study, Porterfield and von Segen (1975) found that hardwood sawlog operations removed 7.3 cubic feet of bark (in-place basis) from the woods with every tree harvested, but pulpwood harvesters took only 3.5 cubic feet of bark from the forest with each hardwood tree harvested; these volumes removed compared to totals of 11.7 and 4.2 cubic feet of bark in entire sawlog and pulpwood stems to a 3-inch top inside bark.

Subsequently in this text each species will be discussed separately (listed alphabetically by common species name). An overview is available, however, from F. G. Manwiller's data on 6-inch hardwoods of 22 species sampled among southern pines throughout each hardwood species' southern range (table 13-4). Stembark in oaks of this size averaged about 20.0 percent (ovendry basis) of above-ground foliage-free tree weight; stembark of the 11 non-oaks averaged 15.3 percent. Branchbark averaged least in yellow-poplar (1.5 percent) and most in post oak (3.9 percent), ovendry-weight basis. See table 13-40 for bark density data that permit weight data of table 13-4 to be converted to in-place volume.

Ash, green.—Six-inch pine-site green ash trees have stembark weight—green (and ovendry) basis—of about 31.6 (16.0) pounds and branchbark weight of about 8.0 (3.6) pounds. Together they total about 13.0 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

For larger green ash trees equation 16-4, with form factors from table 16-10, can be used to compute the volume, ovendry weight, and green weight of stembark.

Ash, white.—Six-inch pine-site white ash trees have stembark weight—green (and ovendry) basis—of about 33.6 (18.5) pounds and branchbark weight of about 6.1 (2.9) pounds. Together they total about 15.5 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

For sawtimber trees sampled in West Virginia and Virginia, Wartluft (1978) found that bark comprised 19 percent of the green weight of tops left after commercial logging.

Elm, American.—Six-inch pine-site American elm trees have stembark weight—green (and ovendry) basis—of about 26.8 (11.9) pounds and branchbark weight of about 7.2 (3.27) pounds; together they total 11.9 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10). For larger American elm trees equation 16-4, with form factors from table 16-10, can be used to compute the volume, ovendry weight, and green weight of stembark.

Elm, winged, and hackberry.—Six-inch pine-site trees of these species have stembark and branchbark weight about as follows (tables 13-4 and 16-8):

Statistic	Winged elm	Hackberry
	Pounds	
Stembark		
Green	23.6	19.1
Ovendry	11.6	10.9
Branchbark		
Green	8.6	6.2
Ovendry	4.1	2.8

Stembark and branchbark together total 11 and 11.6 percent respectively of whole-tree weight of 6-inch winged elm and hackberry, ovendry weight basis.

Hickory sp.—The bark content of 24 **understory** hickory trees 1.0 to 4.9 inches in dbh from the mountains of North Carolina and another 24 from the Upper Piedmont of Georgia and South Carolina was sampled by Phillips (1981); the trees averaged 3 inches in diameter. He found that on an ovendry-weight basis, stems had a lower percentage of bark (27.9–28.1) than branches (32.9–32.4); whole-tree averages for bark content were 28.4 and 28.7 in the two areas (table 13-9). Volume and percentage volume of stem and branches of such trees are given in table !6-7.

Schnell (1978) found that the percentage of bark in hickory stems and branches (i.e., components) decreases with increasing diameter of the component, as follows (ovendry-weight basis):

Component diameter	Bark proportion of component
Inches	*Percent*
<½-1	33
1-2	27
2-3	24
3-4	23
4-5	21
5-8	20
>8	17
Total tree crown	22
Merchantable bole	17

Wartluft (1977) found that whole hickory trees (above-ground parts) measuring **1 to 10 inches in dbh** sampled in West Virginia had 17 percent bark content, green-weight basis.

TABLE 13-9—*Percent bark content (ovendry basis) in understory hardwoods of nine species sampled from two locations* (Phillips 1981)[1]

Species	Stem	Branches	Whole-tree above ground
	Percent		
MOUNTAINS OF NORTH CAROLINA			
Hickory	27.9	32.9	28.5
Maple, red	18.4	25.3	19.7
Oak, chestnut	25.8	36.2	27.0
Oak, white	22.4	33.2	23.9
Tupelo, black	17.6	27.7	19.2
Yellow-poplar	20.3	30.3	21.4
PIEDMONT OF GEORGIA AND SOUTH CAROLINA			
Hickory	28.1	32.4	28.7
Maple, red	14.9	22.5	16.8
Oak, post	20.2	38.2	22.2
Oak, southern red	27.9	30.6	28.3
Oak, white	23.4	35.0	24.7
Sweetgum	22.9	30.6	24.0
Yellow-poplar	21.8	32.2	23.5

[1] Each value is the average for 18 to 25 trees except for post oak which is based on 12 trees. Trees averaged 3 inches in dbh with range from 1 to 4.9 inches.

Six-**inch** pine-site hickory trees have stembark weight—green (and ovendry) basis—of about 45.6 (24.8) pounds and branchbark weight of about 7.5 (3.9) pounds. Together they total 19.1 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

From **12-inch** hickories sampled in Tennessee, Schnell (1978) found that bark on the merchantable stem (8-inch top diameter) accounted for 5 percent of the dry weight of the tree complete with foliage, stump, and roots. This stembark weighed 21 percent as much as the wood in the merchantable stem (ovendry basis). In these 12-inch trees, bark in the crowns weighed twice as much as bark on the merchantable stems.

Table 13-10 shows bark weights per tree reported by Schnell (1978) for hickory **trees 2 to 24 inches in** diameter.

Wiant et al. (1977) reported comparable values for stembark from hickory trees in West Virginia (table 13-11) but less branchbark than reported by Schnell for hickories in Tennessee.

Hickory **tops** residual after logging sawtimber in Virginia and West Virginia were found by Wartluft (1978) to have 26 percent bark content; his data were from only two trees, green-weight basis.

TABLE 13-10—*Weights (ovendry) of stembark and crownbark per tree in hickories of various diameters sampled in Tennessee* (Schnell 1978)

Tree dbh (inches)	Stembark[1]	Crownbark
	Pounds	
2	—	4
4	—	20
6	—	53
8	—	106
10	45	115
12	83	176
14	137	253
16	214	346
18	316	456
20	448	583
22	614	729
24	819	893

[1] To an 8-inch top diameter inside bark.

TABLE 13-11—*Weight (ovendry) of stembark and branchbark per tree of six diameters and eight species sampled in West Virginia* (Wiant et al. 1977)[1,2]

Species and bark component	Tree dbh, inches					
	6	8	10	12	14	16
	Pounds					
Hickory sp.						
Stembark	15	33	60	97	146	208
Branchbark	12	19	26	35	43	53
Maple, red						
Stembark	14	26	52	93	147	216
Branchbark	9	15	23	33	44	56
Oak, black						
Stembark	26	45	78	126	189	267
Branchbark	12	21	34	53	77	105
Oak, chestnut						
Stembark	24	48	83	129	187	259
Branchbark	10	15	27	47	75	110
Oak, northern red						
Stembark	23	44	76	120	174	239
Branchbark	15	22	35	53	77	107
Oak, scarlet						
Stembark	21	41	70	109	159	219
Branchbark	11	17	29	47	72	104

TABLE 13-11—*Weight (ovendry) of stembark and branchbark per tree of six diameters and eight species sampled in West Virginia* (Wiant et al. 1977)[1,2]—Continued

Species and bark component	Tree dbh, inches					
	6	8	10	12	14	16
	Pounds					
Oak, white						
Stembark	12	28	53	91	143	212
Branchbark	8	13	24	40	61	88
Yellow-poplar						
Stembark	20	45	76	110	150	195
Branchbark	4	8	12	16	22	29

[1] Stembark includes bark on stem to a 4-in top diameter outside bark; branchbark includes that on topwood and limbs smaller than 4 inches in diameter outside bark. Data are based on 19 to 22 trees of each species.

[2] See table 16-12 for weight of stemwood and branchwood from these trees, and tables 27-131 and 27-132 for green and ovendry weight of branches with bark included.

Maple, red.—The bark content of 24 **understory** red maple trees 1.0 to 4.9 inches in diameter from the mountains of North Carolina and another 23 from the Upper Piedmont of Georgia and South Carolina was sampled by Phillips (1981); the trees averaged 3 inches in diameter. He found that on an ovendry-weight basis, stems had a lower percentage of bark (18.4–14.9) than branches (25.3–22.5); whole-tree averages for bark content were 19.7 and 16.8 percent in the two areas (table 13-9). Volume and percentage volume of stem and branches of such trees are given in table 16-7.

Young (1971) found the following bark percentages (ovendry-weight basis) in small red maple trees in Maine:

Component	Bark proportion of complete-tree bark exclusive of branches or roots less than ¼-inch in diameter	Bark proportion of component
	Percent	
Merchantable stem	46	13
Branches and unmerchantable top	32	26
Stump and roots	22	15
	100	

Wartluft (1977) found that whole red maple trees (above-ground parts) measuring **1 to 10 inches in dbh** sampled in West Virginia had 16 percent bark content, green-weight basis.

Six-inch pine-site red maple trees have stembark weight—green (and ovendry) basis—of about 27.7 (14.4) pounds and branchbark weight of about 9.1 (3.8) pounds; together they total 13.0 percent of whole-tree weight, ovendry (tables 13-4 and 16-10).

On larger trees **6 to 16 inches in dbh,** Wiant et al. (1977) found that dry weight of red maple stembark varied from 14 to 216 pounds and branchbark from 9 to 56 pounds (table 13-11).

Oak, black.—Six-inch pine-site black oak trees have stembark weight—green (and ovendry basis)—of about 48.7 (27.3) pounds and branchbark weight of about 9.2 (4.4) pounds; together they total 18.7 percent of whole-tree weight, ovendry (tables 13-4 and 16-10).

Schnell (1978) found that the percentage of bark in black oak stems and branches (i.e., components) decreases with increasing average diameter of the component, as follows (ovendry-weight basis):

Component diameter	Bark proportion of component
Inches	*Percent*
<½	32
½–1	27
1–2	23
2–3	23
3–4	23
4–5	22
5–8	22
>8	21
Total tree crown	24
Merchantable bole	11

On trees **6 to 16 inches in dbh,** Wiant et al. (1977) found that dry weight of black oak stembark varied from 26 to 267 pounds and branchbark from 12 to 105 pounds (table 13-11).

On trees **12 to 36 inches in dbh,** the Tennessee Valley Authority (1972) found that dry weight of stembark varied from 93 to 713 pounds and crown bark from 139 to 1,556 pounds (table 16-14). In the 26 trees sampled in North Carolina, Kentucky, and Tennessee, the bark of the merchantable stem was 4 percent of complete-tree weight (including stump-root system) and crown bark averaged twice the weight of stembark (8 percent), ovendry-weight basis. Bark percentage of branches varied by the diameter class of the branch (measured near juncture to stem) as follows, ovendry-weight basis:

Branch size	Bark proportion of branchwood and bark
Inches	*Percent*
<½	36
1–2	28
2–4	27
4–8	25
>8	22

See table 16-15 for limb weights.

Oak, blackjack and cherrybark.—Six-inch pine-site trees of these species have stembark and branchbark weight about as follows (tables 13-4 and 16-10):

Statistic	Blackjack oak	Cherrybark oak
	Pounds	
Stembark		
Green	41.4	34.4
Ovendry	24.2	19.5
Branchbark		
Green	8.8	6.2
Ovendry	4.8	2.9

Stembark and branchbark together total 23.1 percent of whole-tree weight of 6-inch blackjack oak and 14.7 percent of whole-tree weight of 6-inch cherrybark oak, ovendry basis.

Oak, chestnut.—The bark content of 24 **understory** chestnut oaks 1.0 to 4.9 inches in dbh from the mountains of North Carolina was sampled by Phillips (1981); the trees averaged 3 inches in diameter. He found that on an ovendry-weight basis, stems had a lower percentage of bark (25.8) than branches (36.2); whole-tree average bark content was 27.0 percent (table 13-9). Volume and percentage volume of stem and branches of such trees are given in table 16-7.

Average green and dry weights of bark on chestnut oak trees 6 to 20 inches in diameter sampled in western North Carolina, and distribution of the bark in stem and live branches, are given in table 16-17; most of the whole-tree bark is on the stem (60 to 80 percent).

Wartluft (1977) found that whole chestnut oak trees (above-ground parts) measuring **1 to 10 inches in dbh** sampled in West Virginia had 20 percent bark content, green-weight basis.

Ovendry and green weights of whole-tree bark and of branchbark of chestnut oak trees **4 to 5 inches in dbh** are given in table 16-18; values are based on 21 trees sampled in West Virginia.

On trees **6 to 16 inches in dbh,** Wiant et al. (1977) found that dry weight of chestnut oak stembark varied from 24 to 259 pounds and branchbark from 10 to 110 pounds (table 13-11).

Chestnut oak **tops** residual after logging sawtimber in Virginia and West Virginia were found by Wartluft (1978) to have 25 percent bark content; his data were from 16 trees, green-weight basis.

Oak, laurel.—Six-inch pine-site laurel oak trees have stembark weight—green (and ovendry) basis—of about 34.4 (19.6) pounds and branchbark weight of about 7.9 (3.4) pounds. Together they total about 13.5 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

Oak, northern red.—Wartluft (1977) found that whole red oak sp. trees (above-ground parts) measuring **1 to 10 inches in dbh** sampled in West Virginia had 16 percent bark content, green-weight basis.

Six-inch pine site northern red oak trees have stembark weight–green (and ovendry) basis—of about 48.9 (27.6) pounds and branchbark weight of about 7.7 (3.6) pounds; together they total 17.4 percent of whole-tree weight, ovendry (tables 13-4 and 16-10).

On trees **6 to 16 inches in dbh**, sampled in Virginia and West Virginia, Wiant et al. (1977) found that dry weight of northern red oak stembark varied from 23 to 329 pounds and branchbark from 15 to 107 pounds (table 13-11).

Also in West Virginia, Koch (1971b) sampled 10 northern red oaks at each of two locations in each of six diameter classes (4-6, 6-8, 8-10, 10-12, 12-14, and 14-16 inches in dbh). He found that stembark volume (in place) varied from less than a cubic foot on the smallest trees to over 12 cubic feet on the tallest 16-inch trees (table 13-12).

Clark (1978) sampled 71 northern red oaks **6 to 24 inches in dbh** from North Carolina and found that when logged to a 4-in top diameter inside bark, about 15 percent of the material logged is bark and 85 percent is wood. In branches and topwood left as logging residue, about 23 percent by weight is bark and 77 percent wood. When logged to a 4-in top, residual crowns contained 31 to 40 percent of all bark in above-ground tree parts.

Average green and dry weights of bark per tree and distribution of these weights were reported by Clark et al. (1980a) for pulpwood trees (table 13-13) and sawtimber trees (table 13-14) from this same North Carolina sample of northern red oaks. See tables 16-20 and 16-21 for comparable data on weights of wood per tree.

Oak, post.—The bark content of 12 **understory** post oaks 1.0 to 4.9 inches in dbh from the Piedmont of Georgia and South Carolina was sampled by Phillips (1981); the trees averaged 3 inches in diameter. He found that on an ovendry-weight basis, stems had a lower percentage of bark (20.2) than branches (38.2); whole-tree average bark content was 22.2 percent (table 13-9).

Six-inch pine-site post oak trees have stembark weight—green (and ovendry) basis—of about 35.8 (18.9) pounds and branchbark weight of about 10.0 (5.4) pounds. Together they total about 17.7 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

Oak, scarlet.—Six-inch pine-site scarlet oak trees have stembark weight—green (and ovendry) basis—of about 42.1 (23.1) pounds and branchbark weight of about 7.7 (3.3) pounds. Together they total about 16.9 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

On trees **6 to 16 inches in dbh,** Wiant et al. (1977) found that dry weight of scarlet oak stembark varied from 21 to 219 pounds and branchbark from 11 to 104 pounds (table 13-11).

TABLE 13-12—*Stembark volume (6-inch stump to 4-inch top diameter outside bark) on northern red oak and yellow-poplar trees sampled in West Virginia, related to dbh and stem length to a 4-inch top* (Koch 1971b)

Dbh (inches)	Stem length to a 4-inch top										
	10	20	30	40	50	60	70	80	90	100	110
	Cubic feet										
	NORTHERN RED OAK										
4	0.42	0.49	0.55	0.62							
6		.65	.80	.95	1.10	1.25					
8		.89	1.15	1.42	1.69	1.95	2.22				
10		1.19	1.60	2.02	2.44	2.86	3.27	3.86			
12			2.15	2.76	3.36	3.96	4.56	5.16	5.76		
14			2.80	3.62	4.44	5.26	6.07	6.89	7.71	8.53	
16				4.62	5.69	6.76	7.83	8.89	9.96	11.03	12.1
	YELLOW-POPLAR										
4	.45	.53	.62	.71							
6		.75	.95	1.15	1.34	1.54					
8		1.06	1.41	1.76	2.11	2.46	2.81				
10		1.45	2.00	2.55	3.09	3.64	4.19	4.71			
12			2.72	3.51	4.30	5.08	5.87	6.66	7.45		
14			3.58	4.65	5.72	6.79	7.86	8.94	10.01	11.08	
16				5.96	7.36	8.76	10.16	11.56	12.96	14.36	15.76

TABLE 13-13—*Average green and dry weights of bark in whole northern red oak pulpwood trees from North Carolina, and distribution of bark in stem and branches* (Clark et al. 1980a)

D.b.h. class (inches)	Average total height	Sample trees	Whole-tree bark weight	Proportion of bark in—					
				Main stem			Branches (inches d.o.b.)		
				Pulp-wood[1]	Top-wood[2]	Total stem[3]	≥ 2 inches	<2 inches	All crown
	Feet	*Number*	*Pounds*	*Percent*					
				GREEN					
6	61	5	76	60	13	73	5	22	27
7	66	7	104	65	10	75	4	21	25
8	69	7	146	66	7	73	7	20	28
9	75	5	185	65	5	70	10	20	30
10	76	6	229	67	2	69	10	21	31
11	80	6	266	70	2	72	8	20	28
Average	—	—	167	66	6	72	8	20	28
				DRY					
6	61	5	46	60	13	74	5	21	26
7	66	7	63	65	10	75	4	21	25
8	69	7	90	67	7	74	8	18	26
9	75	5	109	66	5	71	10	19	29
10	76	6	139	67	3	70	10	20	30
11	80	6	160	71	2	73	8	19	27
Average	—	—	101	67	6	73	8	19	27

[1] Pulpwood in stem from butt to 4-inch d.i.b. top.

[2] Stem material from 4-inch to 2-inch d.i.b. top.

[3] Main stem to 2-inch d.i.b. top.

TABLE 13-14—*Average green and dry weights of bark in whole northern red oak sawtimber trees from North Carolina, and distribution of bark in stem and branches* (Clark et al. 1980a)

D.b.h. class (inches)	Average total height	Sample trees	Whole-tree bark weight	Proportion of bark in—					
				Main stem			Branches (inches d.o.b.)		
				Saw-log[1]	Pulp-wood[2]	Total stem[3]	≥ 4 inches	<4 inches	All crown
	Feet	*Number*	*Pounds*	*Percent*					
				GREEN					
12	83	5	402	45	19	64	5	31	36
14	94	5	586	51	11	62	10	28	38
16	96	6	656	51	12	63	13	24	37
18	98	6	841	55	9	64	14	22	36
20	102	5	1,047	56	8	64	15	21	36
22	106	5	1,719	52	6	58	21	21	42
24	102	5	1,904	47	9	56	21	23	44
Average	—	—	956	52	9	61	16	23	39
				DRY					
12	83	5	244	46	21	67	5	28	33
14	94	5	369	51	11	67	11	27	38
16	96	6	406	51	12	63	13	24	37
18	98	6	526	55	9	64	14	22	36
20	102	5	646	56	9	65	15	20	35
22	106	5	1,112	52	6	58	21	21	42
24	102	5	1,240	49	8	57	22	21	43
Average	—	—	605	52	9	61	17	22	39

[1] Saw log to 8-inch d.i.b. or saw-log merchantable top.
[2] Pulpwood in stem from saw-log top to 4-inch d.i.b. top.
[3] Main stem to 4-inch d.i.b. top.

Clark et al. (1980b) sampled larger scarlet oaks from the Tennessee Cumberland Plateau. They selected two to four trees from each 2-inch diameter class from 6 to 20 inches dbh. The 28 trees sampled ranged from 37 to 80 years old with average age of 53 years. Green and dry weights of bark in the whole aboveground portions of the trees, and the distribution of the bark are shown in table 13-15. See table 16-16 for comparable data on weights of wood per tree. The main stems of these trees to a 4-in top inside bark had 15 percent of their weight in bark and 85 percent in wood, ovendry basis. In the crowns, 22 percent of the dry weight was bark and 78 percent was wood; this relationship did not vary with tree size. Branches 4 inches in diameter or larger had 20 percent of their green weight in bark; those ½-inch in diameter and smaller had 32 percent of their green weight in bark.

Oak, Shumard.—Six-inch pine-site Shumard oak trees have stembark weight—green (and ovendry) basis—of about 43.6 (24.7) pounds and branchbark weight of about 7.7 (3.5) pounds. Together they total about 15.2 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

Oak, southern red.—The bark content of 25 **understory** southern red oak trees 1.0 to 4.9 inches in dbh from the Piedmont of Georgia and South Carolina were sampled by Phillips (1981); the trees averaged 3 inches in diameter. He found (table 13-9) that on an ovendry-weight basis, stems had a lower percentage of bark (27.9) than branches (30.6). Whole-tree average bark content was 28.3 percent. Volume and percentage volume of stem and branches of such trees are given in table 16-7.

TABLE 13-15—*Average green and dry weight of bark in whole scarlet oak trees (foliage-free above-ground parts) from the Tennessee Cumberland Plateau, and distribution of bark in stem*[1] *and live branches* (Clark et al. 1980b)

D.b.h. class (inches)	Average total height	Sample trees	Whole-tree bark weight	Proportion of bark in—								
				Main stem				Live branches (inches d.o.b.)				
				Saw log[2]	Pulp-wood[3]	Top-wood	Total stem	≥ 4	<4 & ≥ 2	< 2 & > 5	≤ 0.5	All branches
	Feet	*Number*	*Pounds*	*Percent*								
				GREEN PULPWOOD								
6	36	4	66	—	57	21	78	—	0	16	6	22
8	64	4	136	—	62	7	69	—	4	18	9	31
10	68	4	238	—	67	3	70	—	11	13	6	30
Average	—	—	146	—	62	10	72	—	5	16	7	28
				GREEN SAWTIMBER								
12	69	4	360	37	24	2	63	3	12	17	5	37
14	82	4	541	41	19	1	61	9	11	14	5	39
16	86	4	718	45	17	1	63	11	11	11	4	37
18	87	2	860	45	18	1	64	11	11	11	3	36
20	84	2	1,072	38	16	1	55	12	13	14	6	45
Average	—	—	646	42	18	1	61	9	12	13	5	39

See footnotes on next page.

TABLE 13-15—*Average green and dry weight of bark in whole scarlet oak trees (foliage-free above-ground parts) from the Tennessee Cumberland Plateau, and distribution of bark in stem*[1] *and live branches* (Clark et al. 1980b)—Continued

D.b.h. class (inches)	Average total height	Sample trees	Whole-tree bark weight	Proportion of bark in—								
				Main stem				Live branches (inches d.o.b.)				
				Saw log[2]	Pulp-wood[3]	Top-wood	Total stem	≥ 4	<4 & ≥ 2	< 2 & > 5	≤ 0.5	All branches
	Feet	*Number*	*Pounds*	*Percent*								
				DRY PULPWOOD								
6	56	4	41	—	58	21	79	—	0	15	6	21
8	64	4	86	—	63	8	71	—	4	17	8	29
10	68	4	151	—	67	3	70	—	11	13	6	30
Average . . .	—	—	93	—	63	10	73	—	5	15	7	27
				DRY SAWTIMBER								
12	69	4	227	37	25	2	64	3	12	17	4	36
14	82	4	340	41	18	2	61	9	11	14	5	39
16	86	4	451	46	16	1	63	11	11	11	4	37
18	87	2	540	44	18	1	63	11	12	11	3	37
20	84	2	666	39	16	1	56	12	13	13	6	44
Average . . .	—	—	405	42	18	1	61	9	12	13	5	39

[1] Main stem to 2-inch d.i.b. top.

[2] Saw logs to 8-inch d.i.b. or saw-log merchantable top.

[3] Pulpwood in stem from butt or saw-log top to 4-inch d.i.b. top.

Six-inch pine-site southern red oak trees have stembark weight—green (and ovendry) basis— of about 44.4 (24.5) pounds and branchbark weight of about 7.7 (3.9) pounds. Together they total about 20.2 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

Clark et al. (1980c) determined weights and volumes, above stump, of 29 southern red oak trees **5 to 22 inches in dbh** growing in the Highland Rim in Tennessee. Trees sampled ranged from 37 to 100 years of age and averaged 62 years; form class averaged 75. Seventy percent of the average tree's green weight was in stem material to a 4-in top diameter inside bark, and 30 percent was in crown material. Green weight of trees sampled ranged from 279 pounds for 6-in. trees to 7,681 pounds for the 22-in tree. Of the green weight, 13 percent was bark, 46 percent was wood, and 41 percent was water. The proportions of bark did not vary with tree size and ranged from 19 to 21 percent, averaging 19 percent—on a green basis—slightly higher than the average for northern red oak (15 percent) and scarlet oak (16 percent). On an ovendry-weight basis, wood made up an average of 78 percent of whole-tree weight and bark 22 percent (foliage excluded).

Clark et al. found that bark and wood are not distributed evenly throughout the tree. For example, the stem to a 4-in top of the average sawtimber tree contained 73 percent of all the green wood (table 16-23) in the tree but only 60 percent of the bark. The proportions of whole-tree green bark weight in branches increased with tree size, averaging 22 percent in pulpwood trees and 40 percent in sawtimber trees (table 13-16). See table 16-23 for comparable data on weights of wood and its distribution per tree.

Stems to a 4-inch top had 16 percent of their green weight and 20 percent of their ovendry weight in bark. Crowns had 26 percent of their green weight and 27 percent of their ovendry weight in bark. These percentages did not vary consistently with tree size.

TABLE 13-16—*Average green and dry weight of bark in whole southern red oak trees (foliage-free above-ground parts) from the Highland Rim in Tennessee, and distribution of the bark in stem*[1] *and live branches* (Clark et al. 1980c)

D.b.h. class (inches)	Average total height	Sample trees	Whole-tree bark weight	Proportion of bark in—								
				Main stem				Live branches (inches d.o.b.)				
				Saw log[2]	Pulp-wood[3]	Top-wood	Total stem	≥ 4	<4 & ≥ 2	< 2 & > 5	≤ 0.5	All branches
	Feet	*Number*	*Pounds*	*Percent*								
				GREEN PULPWOOD								
6	54	4	66	—	52	23	74	—	6	18	4	26
8	62	4	140	—	69	7	76	—	3	17	4	24
10	72	4	215	—	77	7	84	—	6	10	2	16
Average . . .	—	—	140	—	66	12	78	—	5	14	3	22
				GREEN SAWTIMBER								
12	70	4	394	42	28	3	73	4	12	11	2	26
14	71	4	640	33	24	1	59	8	16	13	2	41
16	76	4	765	34	24	1	60	10	15	12	3	40
18	80	4	1,041	40	17	1	57	15	14	11	2	29
20	—	—	—	—	—	—	—	—	—	—	—	—
22	81	1	1,431	32	24	1	56	17	12	12	3	44
Average . . .	—	—	752	37	22	1	60	13	14	11	2	40

TABLE 13-16—*Average green and dry weight of bark in whole southern red oak trees (foliage-free above-ground parts) from the Highland Rim in Tennessee, and distribution of the bark in stem*[1] *and live branches* (Clark et al. 1980c)—Continued

D.b.h. class (inches)	Average total height	Sample trees	Whole-tree bark weight	Proportion of bark in—								
				Main stem				Live branches (inches d.o.b.)				
				Saw log[2]	Pulp-wood[3]	Top-wood	Total stem	≥ 4	<4 & ≥ 2	< 2 & > 5	≤ 0.5	All branches
	Feet	*Number*	*Pounds*	*Percent*								
				DRY PULPWOOD								
6	54	4	42	—	55	21	76	—	5	17	5	24
8	62	4	96	—	71	7	77	—	2	16	4	22
10	72	4	149	—	78	7	86	—	5	9	2	14
Average	—	—	97	—	68	12	80	—	4	13	3	20
				DRY SAWTIMBER								
12	70	4	273	43	29	3	75	4	12	10	2	25
14	71	4	439	34	25	1	60	9	16	12	2	40
16	76	4	521	35	25	1	61	10	15	11	2	39
18	80	4	709	41	17	1	58	15	14	10	2	41
20	—	—	—	—	—	—	—	—	—	—	—	—
22	81	1	982	33	25	1	58	18	11	11	2	42
Average	—	—	515	37	23	1	61	13	14	10	2	39

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[1] Main stem to 2-inch d.i.b. top.

[2] Saw logs to 8-inch d.i.b. or saw-log merchantable top.

[3] Pulpwood in stem from butt or saw-log top to 4-inch d.i.b. top.

Oak, water.—Six-inch pine-site water oak trees have stembark weight—green (and ovendry) basis—of about 43.2 (24.6) pounds and branchbark weight of about 6.6 (3.2) pounds. Together they total about 15.8 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

Oak, white.—The bark content of **18 understory** white oak trees 1.0 to 4.9 inches in dbh from the mountains of North Carolina and another 23 from the Upper Piedmont of Georgia and South Carolina was sampled by Phillips (1981); the trees averaged 3 inches in dbh. He found that on an ovendry-weight basis, stems had a lower percentage of bark (22.4 and 23.4) than branches (33.2 and 35.0); whole-tree averages for bark content were 23.9 and 24.7 percent in the two areas (table 13-9).

Six-inch pine-site white oak trees have stembark weight—green (and ovendry) basis—of about 27.9 (15.2) pounds and branchbark weight is about 5.8 (3.0) pounds. Together they total 12.6 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

On trees **6 to 16 inches in dbh** in West Virginia, Wiant et al. (1977) found that dry weight of white oak stembark varied from 12 to 212 pounds, and that of branchbark from 8 to 88 pounds (table 13-11). Colannino (1976) provided similar information on West Virginia white oak trees (table 16-18).

Whittaker et al. (1963) sampled ten white oaks near Oak Ridge, Tenn., averaging 96 years old, 73 feet high, and **16.1 inches in diameter.** He found that on an ovendry-weight basis, stembark comprised 12.5 percent of whole-tree above-ground weight (including foliage); stemwood amounted to 58.5 percent of whole-tree weight.

White oak **tops** residual after logging sawtimber in Virginia and West Virginia were found by Wartluft (1978) to have 22 percent bark, green-weight basis; his data came from six trees.

A. Clark III and J. G. Schroeder of the Southeastern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, Asheville, N.C., in personal correspondence during May 1981, provided data on the bark content of 28 white oak trees 6 to 22 inches in dbh sampled on the Nantahala National Forest in North Carolina[3] (table 13-17). See table 16-24 for comparable data on weight of wood and its distribution per tree.

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[3] Clark, A. III, and J. G. Schroeder. Predicted weights and volumes of selected hardwood species in western North Carolina. U.S. Dep. Agric., For. Serv., Res. Pap. Southeast. For. Exp. Stn., Asheville, N.C. (In process.)

TABLE 13-17—*Average green and dry weight of bark of whole white oak trees (foliage-free above-ground parts) from western North Carolina, and distribution of bark in stem*[1] *and live branches* (Unpublished data from A. Clark III and J. G. Schroeder, Southeastern Forest Experiment Station, Asheville, N.C.; see text footnote 3)

Dbh class (inches)	Average total height	Sample trees	Total tree bark weight	Proportion of bark								
				Main Stem				Branches				
				Saw-log[2]	Pulp-wood[3]	Top wood	Total stem	≥ 4	< 4 & ≥ 2	< 2 & > 0.5	≤ 0.5	All branches
	Feet	*Number*	*Pounds*	*Percent*								
				GREEN PULPWOOD								
6..........	49	3	58	—	44	20	64	—	—	26	10	36
8..........	69	3	100	—	64	9	73	—	4	18	5	27
10..........	65	3	192	—	59	4	63	—	13	20	4	37
Average.....	—	-	117	—	56	11	67	—	6	21	6	33
				GREEN SAWTIMBER								
12..........	78	3	377	46	12	2	61	—	14	19	5	39
14..........	97	4	559	40	12	2	60	8	9	17	5	40
16..........	92	3	883	46	7	1	55	10	14	17	4	45
18..........	105	3	1,098	40	9	1	51	20	11	14	3	49
20..........	92	3	1,357	33	13	9	47	22	12	14	4	53
22..........	101	3	1,574	42	8	1	51	21	13	12	3	49
Average.....	—	—	975	41	10	3	54	14	12	16	4	46

See footnotes on next page.

TABLE 13-17—*Average green and dry weight of bark of whole white oak trees (foliage-free above-ground parts) from western North Carolina, and distribution of bark in stem*[1] *and live branches* (Unpublished data from A. Clark III and J. G. Schroeder, Southeastern Forest Experiment Station, Asheville, N.C.; see text footnote 3)—Continued

Dbh class (inches)	Average total height	Sample trees	Total tree bark weight	Proportion of bark								
				Main Stem				Branches				
				Saw-log[2]	Pulp-wood[3]	Top wood	Total stem	≥ 4	< 4 & ≥ 2	< 2 & > 0.5	≤ 0.5	All branches
	Feet	*Number*	*Pounds*	*Percent*								
				DRY PULPWOOD								
6..........	49	3	34	—	47	21	68	—	—	23	9	32
8..........	69	3	59	—	67	9	76	—	3	16	5	24
10..........	65	3	113	—	63	4	67	—	12	18	3	33
Average.....	—	—	69	—	59	11	70	—	5	19	6	30
				DRY SAWTIMBER								
12..........	78	3	213	47	13	2	62	—	14	19	5	38
14..........	97	4	317	47	13	2	62	7	9	16	6	38
16..........	92	3	521	48	7	2	57	10	14	16	3	43
18..........	105	3	629	41	9	1	52	20	11	14	3	48
20..........	92	3	789	34	14	1	49	22	12	14	3	51
22..........	101	3	916	44	8	1	53	20	12	12	3	47
Average.....	—	—	564	43	11	2	56	13	12	15	4	44

[1] Main stem to 2-inch dib top.

[2] Sawlogs to 8-inch dib or merchantable top.

[3] Pulpwood in stem from butt or sawlog top to 4-inch dib top.

Sweetbay.—Six-inch pine-site sweetbay trees have stembark weight—green (and ovendry) basis—of about 34.3 (14.7) pounds and branchbark weight of about 6.7 (2.7) pounds. Together they total 14.2 percent of whole-tree weight, ovendry basis (table 13-4 and 16-10).

Sweetgum.—The bark content of 24 **understory** sweetgum trees 1.0 to 4.9 inches in dbh from the Piedmont of Georgia and South Carolina was sampled by Phillips (1981); the trees averaged 3 inches in dbh. He found that on an ovendry basis, stems had 22.9 percent bark and branches 30.6 percent; whole-tree average for bark content was 24.0 percent (table 13-9).

Average green and dry weights of bark on sweetgum trees **6 to 20 inches in diameter** sampled in the Georgia Piedmont, and distribution of the bark in stem and live branches, are given in table 16-26; more than half the whole-tree bark is on the stem.

6-inch pine-site sweetgum trees have stembark weight—green (and ovendry) basis—of about 22.7 (11.8) pounds and branchbark weight of about 5.2 (1.9) pounds. Together they total 14.2 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

For larger sweetgum trees in Mississippi, equation 16-4 with form factors from table 16-13, can be used to compute the volume, ovendry weight, and green weight of stembark.

Tupelo, black.—The bark content of 18 **understory** black tupelo trees 1.0 to 4.9 inches in dbh from the mountains of North Carolina was sampled by Phillips (1981); the trees averaged 3 inches in dbh. He found that on an ovendry basis, stems had 17.6 percent bark and branches 27.7 percent; whole-tree average for bark was 19.2 percent (table 13-9).

Six-inch pine-site black tupelo trees have stembark weight—green (and ovendry) basis—of about 27.8 (13.7) pounds and branchbark weight of about 6.1 (2.4) pounds. Together they total 14.8 percent of whole-tree weight, ovendry basis (tables 13-4 and 16-10).

Yellow-poplar.—The bark content of 24 **understory** yellow-poplar trees 1.0 to 4.9 inches in dbh from the mountains of North Carolina, and another 24 from the Upper Piedmont of Georgia and South Carolina was sampled by Phillips (1981); the trees averaged 3.0 inches in dbh. He found that on an ovendry-weight basis, stems had 20.3 and 21.8 percent bark while branches had 30.3 and 32.2 percent; whole-tree averages for bark content were 21.4 and 23.5 percent in the two areas.

Wartluft (1977) found that whole yellow-poplar trees (above-ground parts) measuring **1 to 10 inches in dbh** sampled in West Virginia had 19 percent bark, green-weight basis.

Six-inch pine-site yellow-poplar trees have stembark weight—green (and ovendry) basis—of about 44.0 (17.4) pounds and branchbark weight of about 5.0 (1.9) pounds. Together they total 15.6 percent of whole-tree weight, ovendry (tables 13-4 and 16-10).

On larger trees **6 to 16 inches in dbh,** Wiant et al. (1977) found that ovendry weight of yellow-poplar stembark varied from 20 to 195 pounds and branchbark from 4 to 29 pounds (table 13-11).

Whittaker et al. (1963) sampled 10 yellow-poplars near Oak Ridge, Tenn., averaging 75 years old, 75 feet high, and **13.3 inches in dbh;** they found that stembark comprised 9.2 percent of above-ground tree weight (foliage included) and that stemwood was 76.4 percent, ovendry-weight basis.

Clark (1978) found that logging yellow-poplar stems to a 4-inch top removes 65 to 85 percent of all the wood, basis of ovendry weight, in **pulpwood-size trees** 5.0 to 10.9 inches in dbh, and 88 to 93 percent of wood in **sawtimber size trees** 11 inches and larger in dbh. When stems are logged to a 4-inch top, about 15 percent of the material harvested is bark and 85 percent is wood. The branches and topwood left as logging residue contain about 23 percent of their weight in bark and 77 percent in wood. The foregoing data are all on the basis of ovendry weights.

Yellow-poplar **tops** residual after logging sawtimber in Virginia and West Virginia were found by Wartluft (1978) to have 28 percent bark content; his data are from 14 trees, green-weight basis.

Clark and Schroeder (1977) analyzed the foliage-free, above-ground biomass of 39 yellow-poplar trees **6 to 28 inches in dbh** growing in natural, unevenaged mountain cove stands in western North Carolina. Their findings are summarized in tables 16-27 through 16-30 and related discussion.

BARK VOLUME AND WEIGHT PER LOG

Weights of bark ascertained in the laboratory from measurements of tree components differ from weights of bark removed by debarkers during sawmill operations because bark removal in the mill may be incomplete or some wood may be removed with the bark. Completeness of bark removal varies with species, season, machine type, and operator.

Wartluft (1972) measured ovendry weights of bark removed from West Virginia logs of eight species by two debarker types:

- rosser head—in which a toothed cutterhead presses down on the top of the log and is traversed the length of the log as the log rotates beneath it.
- floating cutterhead—in which the cutterhead presses upward against the log which is rotated and traversed past the cutterhead.

Data were collected in the fall season from logs with no excessive dirt or mud and with at least three-fourths of the bark intact. He found that the average percent wood in the bark residue was 31.5 percent for the floating-cutterhead debarker and 8.5 percent for the rosser-head machine. In the two mills studied, Wartluft estimated that about one-third the bark remained on logs after they passed through the debarking machines. Bark residues removed by the rosser-head debarker varied with species (fig. 13-66) but it averaged about 75, 125, and 150 pounds per log of 100, 200, and 300 board feet Doyle scale, ovendry-weight basis.

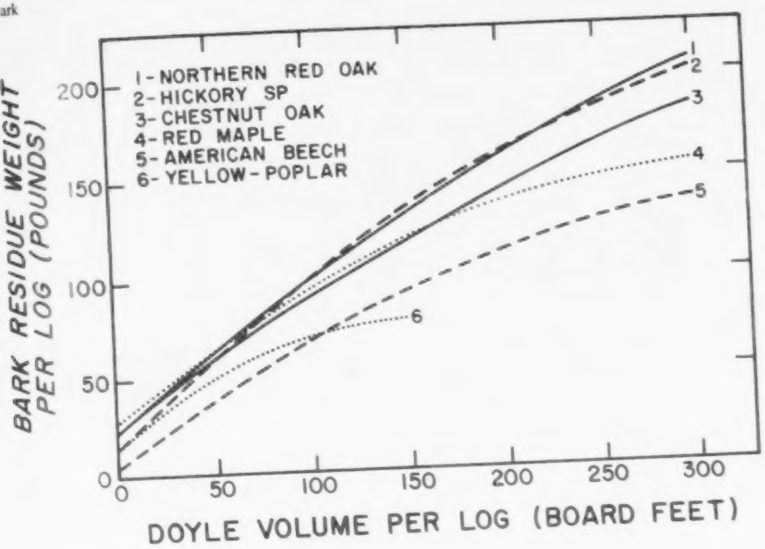

Figure 13-66.—Relationship between bark residue weight (ovendry basis) and Doyle volume per log for six West Virginia hardwood species debarked in fall season on a rosser-head debarker. (Drawing after Wartluft 1972.)

In a similar study, Massengale (1971) measured the green weight of bark residue removed by mechanical debarkers of floating-cutterhead type from oak logs of mixed species harvested in the Missouri Ozarks. His data (table 13-18), based on twenty logs, 8 feet long, in each 1-inch-diameter class from 8 to 16 inches, and 11 and five logs of the 17- and 18-inch classes, respectively, show that weight of bark residue removed per log varies greatly with log diameter and length, and that ovendry bark residue weight is about 68 percent of its green weight.

On black oak trees 12 to 36 inches in dbh, the Tennessee Valley Authority (1972) found that dry weight of stembark varied from 93 to 713 pounds (table 16-11); these data were based on laboratory measurements of bark weight and not on mill studies of debarking equipment.

Phillips (1975) analyzed lumber and residue yields of 130 black oak sawlogs 9 to 21 inches in scaling diameter, debarked with a rosser head, and processed through a bandsaw headrig in western North Carolina. He found that green weight of bark residue per log could be predicted by the following equation ($R^2 = 0.89$; standard error of estimate = 28.7 pounds):

$$\hat{Y} = 42.50776 + 0.05526\ D^2L \tag{13-3}$$

where:

D = sawlog scaling diameter, inches
L = sawlog length, feet
$\hat{Y}$ = green bark residue per log, pounds

In Phillips' study, the bark residue was about 80 percent bark and 20 percent wood. His predicted data are summarized in table 13-19. Green bark residue averaged 15.3 percent of green log weight with bark.

TABLE 13-18—*Weight (green) of bark removed by mechanical debarkers of floating-cutterhead type from oak logs of mixed species from the Missouri Ozarks, related to their diameter and length* (Massengale 1971)[1]

Log scaling diameter (inches)	Log length, feet				
	8	10	12	14	16
	Pounds of bark per log				
8	30	44	58	73	87
9	44	62	79	96	114
10	57	78	99	119	140
11	70	94	118	142	166
12	83	110	137	165	192
13	96	126	157	188	218
14	109	143	176	210	244
15	122	159	196	233	270
16	135	175	215	256	296
17	148	193	230	280	322
18	161	211	251	305	349

[1] Average bark moisture content was 48.7 percent of ovendry weight.

TABLE 13-19—*Predicted weight (green) of bark residue*[1] *removed by a rosser-head debarker from black oak sawlogs from western North Carolina, related to scaling diameter and length* (Phillips 1975)[2]

Scaling diameter (inches)	Sawlog length, feet					
	8	10	12	14	16	18
	Pounds per log					
8	71	78	85	92	99	106
10	87	98	109	120	131	142
12	106	122	138	154	170	186
14	129	151	172	194	216	237
16	156	184	212	241	269	297
18	186	222	257	293	329	365
20	219	264	308	352	396	440
22	256	310	363	417	470	524
24	297	361	424	488	552	615

[1] Eighty percent bark and 20 percent wood.

[2] This table, constructed from equation 13-3, is based on data from logs mostly 10 to 16 feet long and 9 to 21 inches in diameter.

In a related study, Phillips et al. (1974) determined that bark residue removed by a rosser-head debarker from merchantable stems of black oak harvested in western North Carolina could be predicted by the following equation (R^2 = 0.95; standard error of the estimate = 74.5 pounds):

$$\hat{Y} = 77.43299 + 0.03224\,(dbh)^2 Mh \qquad (13\text{-}4)$$

where:

dbh = tree diameter at breast height, inches

Mh = merchantable tree height (including 1-foot stump height) to about a 12-inch top dib, feet; a one-log tree has a merchantable height of about 17 feet, a two-log tree 33 feet.

$\hat{Y}$ = bark residue per merchantable stem, pounds (green basis)

Equations predicting bark weights and volumes on merchantable stems of four important southern hardwoods can be found in the following tables (based on laboratory measurements, not bark residues from debarking equipment):

Species	Tables (for equations)	Tables (for computed values)
Oak, northern red	27-65A	13-14, 27-66A
Oak, scarlet	27-65B	13-15, 27-66B
Oak, southern red	27-65C	13-16, 27-66C
Sweetgum	—	16-26
Yellow-poplar	16-29, 16-30	27-66D

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Clark (1976) analyzed lumber and residue yields of 230 yellow-poplar sawlogs 7 to 23 inches in scaling diameter, debarked with a rosser-head, and processed through a bandsaw headrig in western North Carolina. He found that green weight of bark residue per log could be predicted by the following equation ($R^2 = 0.97$):

$$\hat{Y} = 25.22305 + 0.04371D^2L \qquad (13\text{-}5)$$

where:

D = sawlog scaling diameter, inches
L = sawlog length, feet
$\hat{Y}$ = green bark residue per log, pounds

In Clark's study, the bark residue was estimated to be 97 percent bark and 3 percent wood. His predicted data are summarized in table 13-20. Green bark residue averaged 15 percent of green log weight with bark. The bark residue averaged 105 percent moisture content, ovendry-weight basis and had bulk density when green of 40.2 lb/cu ft.

In a related study of 47 trees 12 to 26 inches in dbh Clark et al. (1974) determined that bark residue removed by a rosser-head debarker from merchantable stems of yellow-poplar trees harvested in western North Carolina could be predicted by the following equation ($R^2 = 0.98$):

$$\hat{Y} = 85.79319 + 0.02255\,(\text{dbh})^2\,\text{Mh} \qquad (13\text{-}6)$$

where:

dbh = tree diameter at breast height, inches
Mh = merchantable tree height to about 9.5-inch top dib, feet
$\hat{Y}$ = bark residue per merchantable stem, pounds (green basis)

TABLE 13-20—*Predicted weight (green) of bark residue*[1] *removed by a rosser-head debarker from yellow-poplar sawlogs from western North Carolina, related to scaling diameter and length* (Clark 1976)[2]

Scaling diameter (inches)	Sawlog length, feet 8	10	12	14	16
	Pounds per log				
8	48	53	59	64	70
10	60	69	78	86	95
12	76	88	101	113	126
14	94	111	128	145	162
16	115	137	160	182	204
18	139	167	195	223	252
20	165	200	235	270	305
22	194	237	279	321	364
24	227	277	327	378	428

[1] Estimated to be 97 percent bark and 3 percent wood.

[2] The table, constructed from equation 13-5, is based on data from 230 sawlogs, mostly 10 to 16 feet long and 8 to 21 inches in diameter.

BARK VOLUME AND WEIGHT PER STANDARD ROUGH CORD

A **standard cord** of pulpwood is a stack of 4-ft lengths of rough wood (bark in place) in a pile 4 ft high and 8 ft. long. The 128 cu. ft. in such a stack is filled in part with bark, and in part with voids between the sticks. Volume of wood in a standard cord is maximum if wood is compactly piled, thin-barked, well-trimmed, straight, and of large diameter (tables 27-1 and 27-2). Depending on the foregoing factors, a standard cord of rough wood may contain from 55 to 95 cu. ft. of wood, free of bark and voids. The in-place volume of bark will vary with volume of wood and with species and cannot easily be measured after removal due to fracturing and distortion. However, assuming that the ratio (k) of stick diameter inside bark to diameter outside bark is approximately constant at the values in table 13-4, then bark volume in a standard rough cord can be computed for various volumes per cord of bark-free wood (table 13-21). For bark volume per cord at other values of k refer to table 27-3.

Wood volumes per cord should be least in piles of thick-barked wood such as blackjack oak and most in piles of thin-barked species such as red maple and hackberry, if wood is uniformly piled and of comparable diameter, straightness, and smoothness. Chamberlain and Meyer (1950) replicated piles of hardwood pulpwood harvested in Pennsylvania, including four species that grow in the South, and found that bark volume expressed as a percentage of rough wood (wood plus bark) volume varied from about 11 percent in piles of red maple to nearly 20 percent in piles of black oak or white oak (table 13-22); unstated in this report was the volume of wood and bark per standard cord of these species.

TABLE 13-21—*Volume of bark (in-place) in stacked rough cords of small pine-site hardwood pulpwood related to volume of wood (bark free) in the cord and to species*[1]

Species	Ratio of bark volume to wood volume[1]	Volume of wood free of bark and voids per cord, cubic feet 55	65	75	85	95
		Cubic feet of bark/cord				
Ash, green	0.197	10.8	12.8	14.8	16.7	18.7
Ash, white	.330	18.2	21.4	24.8	28.0	31.4
Elm, American	.141	7.8	9.2	10.6	12.0	13.4
Elm, winged	.176	9.7	11.4	13.2	15.0	16.7
Hackberry[2]	.096	5.3	6.2	7.2	8.2	9.1
Hickory sp.	.235	12.9	15.3	17.6	20.0	22.3
Maple, red	.110	6.1	7.2	8.3	9.4	10.5
Oak, black	.271	14.9	17.6	20.3	23.0	25.7
Oak, blackjack	.434	23.9	28.2	32.6	36.9	41.2
Oak, cherrybark	.166	9.1	10.8	12.4	14.1	15.8
Oak, laurel	.127	7.0	8.2	9.5	10.8	12.1
Oak, northern red	.213	11.7	13.8	16.0	18.1	20.2
Oak, post	.254	14.0	16.5	19.0	21.6	24.1
Oak, scarlet	.202	11.1	13.1	15.2	17.2	19.2
Oak, Shumard	.176	9.7	11.4	13.2	15.0	16.7
Oak, southern red	.286	15.7	18.6	21.4	24.3	27.2
Oak, water	.164	9.0	10.7	12.3	13.9	15.6
Oak, white	.149	8.2	9.7	11.2	12.7	14.2
Sweetbay	.156	8.6	10.1	11.7	13.3	14.8
Sweetgum	.218	12.0	14.2	16.4	18.5	20.7
Tupelo, black	.182	10.0	11.8	13.6	15.5	17.3
Yellow-poplar	.200	11.0	13.0	15.0	17.0	19.0

[1] Based on the relationship:

$$\frac{\text{Volume of bark}}{\text{Volume of wood}} = \frac{1}{k^2} - 1$$

where k is the ratio of diameter inside bark to diameter outside bark; see table 13-4.

[2] Mostly sugarberry.

TABLE 13-22—*Bark volume as a percent of volume of wood and bark in pulpwood piles of four species* (Chamberlain and Meyer 1950)

Species and pile replication	Bark volume
	---Percent--
Maple, red	
1	11.3
2	12.6
3	8.9
4	14.5
5	7.2
Average	10.9
Oak, black	
1	22.5
2	17.1
Average	19.8
Oak, scarlet	
1	14.5
2	20.9
3	14.3
Average	16.6
Oak, white	
1	20.5
2	19.5
3	19.6
4	14.0
5	19.9
6	23.4
Average	19.5

Weight of bark per cord.—Clark et al. (1980abc) provided data on the green weight of wood and bark per cubic foot of wood of three southern oaks (table 13-23). For similar data on chestnut and white oak and sweetgum, see table 7-2A; for comparable data applicable to the hard hardwoods and soft hardwoods of north-central Louisiana, see table 27-101. These data permit computation of the weight of a rough green cord of pulpwood of these species (sticks 4- to 8-inch top dib) containing varying volumes of wood free of bark (table 13-24). For typical volumes of wood and bark per hardwood standard rough cord, see tables 27-1 and 27-2.

It is evident that the green weight of a rough cord of wood varies with species and content of wood free of bark. Because the ratio of weight of stembark to stemwood varies with species (table 13-25), the weight of stembark per cord must also vary. The problem can be simplified by assuming that a cord of rough green wood weighs 6,000 pounds. The weight of bark per cord of small pine-site hardwood stemwood will then be as given in table 13-25. For other weights per cord (Wiant and Wingerd 1981, for example, suggest 5,809 pounds as average for green Appalachian hardwoods), the weight of bark per cord can be adjusted in direct proportion. Pulpwood of larger diameter will have less bark per cord than indicated in table 13-25. The values tabulated are laboratory-measured; weights removed by debarkers in a mill will be different.

TABLE 13-23—*Average green weight of wood and bark per cubic foot of wood and average weight of wood and bark per cubic foot of wood and bark for three oak species and their components sampled in the South* (Clark et al. 1980 abc)

Species and tree component	Green weight of wood and bark per cubic foot of wood[1]	Green weight of wood and bark per cubic foot of wood and bark[1]
	Pounds	
Northern red oak[2]		
Whole tree	77 ± 1.9	65 ± 1.4
Stem (butt to 4-inch top dib)	75 ± 1.9	65 ± 1.5
Sawlog (butt to 8-inch top dib)	75 ± 1.8	65 ± 1.5
Pulpwood (8- to 4-inch top dib)	78 ± 3.2	65 ± 1.6
Branches	83 ± 3.2	63 ± 1.7
Scarlet oak[3]		
Whole tree	79 ± 1.7	66 ± 1.4
Stem (butt to 4-inch top dib)	78 ± 2.3	66 ± 1.4
Sawlog (butt to 8-inch top dib)	77 ± 2.7	67 ± 1.7
Pulpwood (8- to 4-inch dib)	82 ± 3.8	64 ± 1.8
Topwood (4- to 2-inch top dib)	87 ± 6.6	64 ± 2.6
Branches	84 ± 3.0	64 ± 2.6
Southern red oak[4]		
Whole tree	81 ± 1.9	64 ± 1.5
Stem (butt to 4-inch top dib)	79 ± 1.9	64 ± 1.6
Sawlog (butt to 8-inch top dib)	79 ± 1.8	65 ± 1.3
Pulpwood (8- to 4-inch top dib)	82 ± 3.8	64 ± 1.8
Topwood (4- to 2-inch top dib)	87 ± 6.6	64 ± 2.6
Branches	88 ± 4.3	64 ± 1.6

[1] The first value is the average, followed by standard deviation.

[2] From western North Carolina.

[3] From the Tennessee Cumberland Plateau.

[4] From the Highland Rim in Tennessee.

TABLE 13-24—*Weights per cord of rough green oak pulpwood of five solidwood contents and three species*[1]

Species	Volume of wood (bark free) per rough cord, cubic feet				
	55	65	75	85	95
	Cord weight green, pounds				
Northern red oak	4,290	5,070	5,850	6,630	7,410
Scarlet oak	4,345	5,135	5,925	6,715	7,505
Southern red oak	4,510	5,330	6,150	6,970	7,790

[1] Derived from pulpwood (8- to 4-inch dib) data in table 13-23.

TABLE 13-25—*Weight of bark, green and ovendry, per 6,000-pound rough green cord of hardwood from small pine-site trees, related to species*[1]

Species	Ratio of stembark weight to stemwood weight, green basis	Ratio of stembark weight dry to stembark weight green	Bark weight/cord when Green	Bark weight/cord when Ovendry
			Pounds	Pounds
Ash, green	0.19	0.51	958	489
Ash, white	.22	.55	1,082	595
Elm, American	.16	.44	828	364
Elm, winged	.13	.49	690	338
Hackberry[2]	.13	.57	690	393
Hickory sp.	.28	.54	1,313	709
Maple, red	.16	.52	828	431
Oak, black	.25	.56	1,200	672
Oak, blackjack	.31	.58	1,420	824
Oak, cherrybark	.18	.57	915	522
Oak, laurel	.16	.57	828	472
Oak, northern red	.22	.56	1,082	606
Oak, post	.24	.53	1,161	615
Oak, scarlet	.23	.55	1,122	617
Oak, Shumard	.19	.57	958	546
Oak, southern red	.28	.55	1,313	722
Oak, water	.19	.57	958	546
Oak, white	.15	.54	783	423
Sweetbay	.18	.43	915	393
Sweetgum	.14	.52	737	383
Tupelo, black	.18	.49	915	448
Yellow-poplar	.22	.40	1,082	433

[1] Derived from table 16-10.

[2] Mostly sugarberry.

BARK WEIGHT PER Mbf LOG SCALE

The weight of bark removed from sawlogs per Mbf log scale varies with species, log diameter, effectiveness of debarking equipment, and with log scale.

Wartluft (1974a) measured bark residue green weights from 686 sawlogs of six hardwood species groups at four sawmills in West Virginia, two with floating cutterhead debarkers and two with rosser-head debarkers (table 13-26). He found that the average green weight of hardwood bark residue per 1,000 board feet (log rule) from all study logs of all species was:

Log rule	Pounds
Doyle	1,534
Scribner decimal C	1,255
International ¼-inch	1,164

This weight of residue averaged 11 percent of total log weight. The moisture content of the bark residue averaged 68 percent, ovendry weight basis.

TABLE 13-26—*Bark residue weights (green basis) per log related to species group and log volume by three log scales* (Wartluft 1974a)[1]

Log volume (board feet)	Red oak sp.[2]	Chestnut oak, white oak, and hickory[3]	Maple sp.[4]	Beech[5]	Yellow-poplar[6]	Basswood[7]
	Pounds					
			DOYLE LOG RULE			
20	70	64	68	35	53	71
40	92	81	89	57	74	87
60	113	99	108	77	94	103
80	135	116	126	96	115	119
100	157	134	142	114	136	134
120	179	151	157	130	157	150
140	201	168	169	146	177	166
160	223	186	181	160	198	182
180	245	203	190	172	219	198
200	266	221	198	184	240	213
220	288	238	204	194	260	229
240	310	255	208	203	281	245
260	332	273	211	210	302	261
280	354	290	212	217	322	277
300	376	308	212	222	343	292
			INTERNATIONAL ¼-INCH RULE			
20	51	47	45	17	37	60
40	72	64	67	38	55	74
60	92	81	88	57	73	88
80	112	97	107	75	91	102
100	133	114	124	92	109	116
120	153	131	140	109	127	130
140	173	148	154	124	145	144
160	193	165	167	138	163	158
180	214	182	178	151	181	172
200	234	198	188	164	199	186
220	254	215	196	175	217	200
240	274	232	202	186	235	214
260	295	249	207	195	253	228
280	315	266	210	203	271	242
300	335	283	212	211	289	256

See footnotes at end of table.

TABLE 13-26—*Bark residue weights (green basis) per log related to species group and log volume by three log scales* (Wartluft 1974a)[1]—Continued

Log volume (board feet)	Red oak sp.[2]	Chestnut oak, white oak, and hickory[3]	Maple sp.[4]	Beech[5]	Yellow-poplar[6]	Basswood[7]
	Pounds					
	SCRIBNER DECIMAL C RULE					
20	55	50	51	20	39	62
40	76	68	73	41	58	77
60	97	85	93	62	78	92
80	119	103	112	81	97	106
100	140	120	130	99	117	121
120	161	138	145	115	137	136
140	183	155	159	131	156	151
160	204	173	172	146	176	165
180	225	190	182	159	195	180
200	247	208	192	172	215	195
220	268	225	199	183	234	210
240	289	243	205	193	254	224
260	311	260	209	202	273	239
280	332	278	212	210	293	254
300	353	295	212	217	312	269

[1] Green weight at average moisture content for each species and species group. Values computed using regression equations.

[2] *Quercus* sp.; 63 percent moisture content; bulk density 509 lb/cu yard, green.

[3] 59 percent moisture content. Bulk density of green bark residue per cubic yard was 457 for chestnut oak, 439 for white oak, and 287 for hickory sp.

[4] *Acer* sp.; 55 percent moisture content; bulk density of 625 lb/cu yard, green.

[5] *Fagus grandifolia* Ehrh.; 68 percent moisture content; bulk density of 717 lb/cu yard, green.

[6] 96 percent moisture content; bulk density of 419 lb/cu yard, green.

[7] *Tilia americana* L.; moisture content 114 percent; bulk density 250 lb/cu yard, green.

Cassens and Choong (1976) measured the green weight of bark residue from two mills cutting hardwood sawlogs from the Mississippi Delta near Baton Rouge, La. Of the six species groups measured (table 13-27) bark residue per thousand board feet Doyle log scale was least for sweetgum and white oak (about 950 pounds); the maximum (about 1,300 pounds) was from small ash, elm, and tupelo logs.

BARK WEIGHT PER Mbf LUMBER SCALE

Massengale (1971) found that weight (green) of bark removed by mechanical debarkers from oak logs of mixed species harvested and sawn on a circular-saw headrig in the Missouri Ozarks averaged about 2,042 pounds per thousand board feet of lumber sawn. His data were based on twenty 8-foot-long logs in each 1-inch-diameter class from 8 to 16 inches and 5 logs in the 17- and 18-inch classes. No clear relationship between log diameter and bark yield per Mbf of lumber was discernible (table 13-28). The bark weights noted by Massengale are considerably greater than would be expected from data of Wartluft (table 13-26; see International ¼-inch scale) and Cassens and Choong (table 13-27). With circular-saw headrigs, mills should cut about 1 Mbf lumber from 1 Mbf of logs scaled by the International ¼-inch scale, and more than 1 Mbf lumber from sawlogs scaled by the Doyle rule.

Phillips (1975), in his study of residue yields of 130 black oak sawlogs 9 to 21 inches in scaling diameter harvested in western North Carolina, found that bark residue produced by a rosser-head debarker per Mbf of lumber sawn in a mill with a bandsaw headrig decreased as log diameter and length increased (table 13-28).

Page and Baxter (1974) concluded that 0.44 to 0.70 ton of bark, green basis, is produced for each thousand board feet of southern hardwood lumber sawn.

TABLE 13-27—*Bark residue weights (green basis) per Mbf Doyle log scale related to species group, log diameter, and mill* (Cassens and Choong 1976)

Species group and mill number[1]	Average log scaling diameter	Weight of fresh (green) bark per Mbf of logs, Doyle log scale[2]
	Inches	*Pounds*
Ash sp.		
1	12.2	1,322
2	14.8	1,297
Elm sp.		
1	13.3	1,316
2	—	—
Oak, red sp.		
1	15.2	1,227
2	19.3	1,184
Oak, white		
1	15.1	936
2	—	—
Sweetgum		
1	12.6	979
2	14.8	921
Tupelo sp.		
1	12.3	1,316
2	13.7	1,001

[1] Logs were harvested on the Mississippi Delta near Baton Rouge, La.

[2] Based on laboratory computations from log measurements taken at mill; bark residues from mill debarkers were not weighed.

TABLE 13-28—*Weight of bark residue (green) removed by a mechanical debarker from oak logs of mixed species per Mbf of lumber sawn* (Massengale 1971)[1]

Log scaling diameter (inches)	Bark residue (green) per Mbf lumber
	Pounds
8	2,460
9	2,500
10	2,480
11	1,680
12	2,060
13	1,900
14	2,220
15	1,740
16	1,700
17	1,790
18	1,930

[1] Logs were harvested in the Missouri Ozarks, debarked on a floating-cutterhead type barker, and sawn into lumber on a circular-saw headrig. Data are based on 190 8-foot-long logs.

TABLE 13-29—*Weight of bark residue (green) removed by a rosser-head debarker from black oak logs per Mbf of lumber sawn*[1] (Phillips 1975)

Log scaling diameter (inches)	Sawlog length, feet				
	8	10	12	14	16
	Pounds of bark				
8	10,142	6,000	4,478	2,838	3,194
10	4,143	3,267	2,725	2,449	2,220
12	2,865	2,392	2,123	1,974	1,848
14	2,263	1,987	1,830	1,717	1,636
16	1,950	1,769	1,643	1,575	1,520
18	1,755	1,620	1,539	1,480	1,437
20	1,622	1,526	1,460	1,414	1,380
22	1,533	1,455	1,402	1,367	1,339
24	1,470	1,410	1,363	1,333	1,311

[1] Data based on regression analyses of results of sawing 130 logs from western North Carolina in a mill with bandsaw headrig.

13-4 MOISTURE CONTENT OF BARK

Data in this section are applicable to whole bark, i.e., inner bark and rhytidome combined; no data are published on moisture content variation from inner bark across the rhytidome of southern hardwoods. Inner bark typically should have much higher moisture content than rhytidome. See figure 12-21 from 496 of Koch (1972) for inner bark moisture content of southern pine.

MOISTURE CONTENT OF BARK IN LIVING TREES

Moisture content of bark vs. that of wood.—In the 11 oaks under study, and in sweetgum and black tupelo, average stembark moisture content of live 6-inch pine-site trees is lower than that of stemwood; in the ashes, elms, hickories, red maple, sweetbay, and yellow-poplar, however, stembark of such small trees has higher moisture content than stemwood. Branchbark has higher moisture content than branchwood except in blackjack oak, sweetgum, and black tupelo (table 8-2).

The relationships may change with height in the stem. In 50-year-old yellow-poplar averaging about 10 inches in dbh, Phillips and Schroeder (1973) found that stembark had less moisture content than heartwood and sapwood up to about 15 percent of total tree height; above 50 percent of total tree height bark moisture content exceeded the moisture content of both sapwood and heartwood (fig. 8-4).

D. R. Phillips (unpublished data of September 2, 1981) found the following moisture contents in wood and bark of understory hardwoods 1.0 to 4.9 inches in dbh sampled in the Piedmont of South Carolina:

Species and tree component	Bark moisture content	Wood moisture content	Bark proportion (dry-weight basis)
	------Percent of ovendry weight------		*Percent*
Hickory sp.			
Stem	66.1	50.8	29.3
Branch	89.6	50.1	38.8
Whole tree above ground	69.1	50.7	30.4
Maple, red			
Stem	89.2	84.9	15.2
Branch	111.6	83.6	26.2
Whole tree above ground	94.4	84.9	17.8
Oak, post			
Stem	65.5	69.2	19.8
Branch	72.5	60.7	39.6
Whole tree above ground	66.7	68.2	22.0
Oak, southern red			
Stem	56.9	68.5	24.7
Branch	67.5	52.3	33.3
Whole tree above ground	58.8	66.6	25.9
Oak, white			
Stem	68.4	61.8	19.8
Branch	81.2	61.2	34.0
Whole tree above ground	69.8	61.7	21.5
Sweetgum			
Stem	88.4	124.7	20.0
Branch	139.6	105.1	35.1
Whole tree above ground	121.6	121.6	21.9
Yellow-poplar			
Stem	147.1	127.8	23.4
Branch	168.2	119.7	36.1
Whole tree above ground	149.7	126.7	25.0

Seasonal variation.—Data on seasonal variation of bark moisture content in southern hardwoods are limited. Phillips and Schroeder (1973) found from analysis of 60 yellow-poplar trees in a 50-year-old second-growth stand in the southern Appalachian Mountains of North Carolina that stembark moisture content was significantly higher in June and significantly lower in October than at other times in the year; the pattern of seasonal variation was the same at all heights in the tree (fig. 13-67).

G. E. Woodson (table 17-1) found that breast height samples of bark from 13 species of hardwoods growing among southern pines in central Louisiana had average moisture content of 51 percent in September, 57 percent in February, and 63 percent in June (overdry-weight basis).

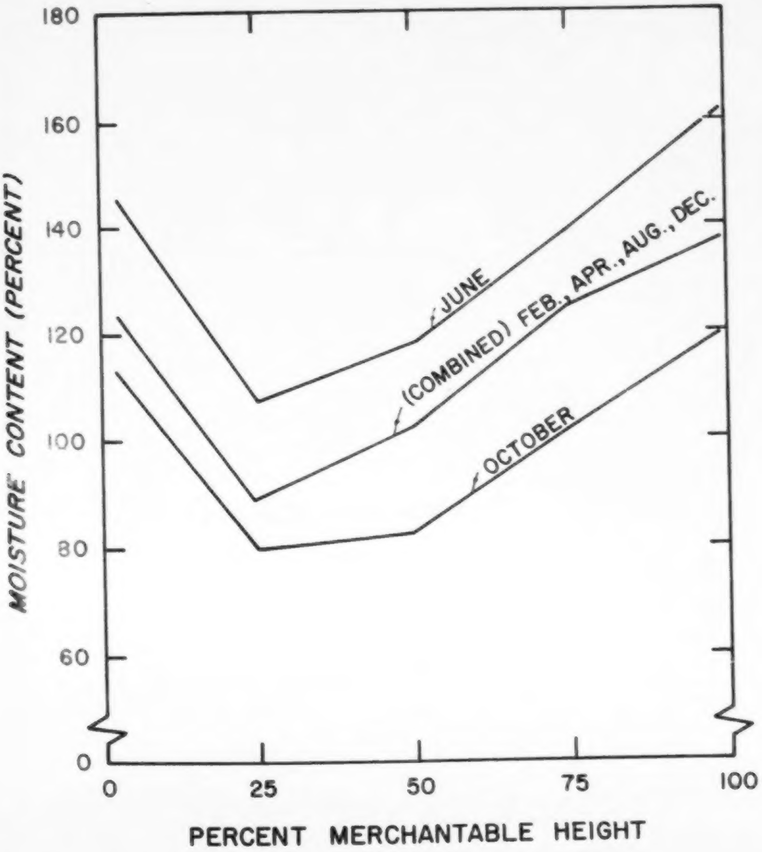

Figure 13-67.—Moisture content of yellow-poplar bark related to height in tree and season of year. (Drawing after Phillips and Schroeder 1973.)

Variation with height in tree.—In their study, Phillips and Schroeder (1973) also found that bark moisture content was lowest at about 25 percent of merchantable height and highest near ground level and in the upper stem (fig. 13-67).

Variation with tree diameter at sample point.—Wartluft (1977) sampled 200 small hardwoods near Richwood, West Virginia—20 in each 1-in dbh class from 1 to 10 in. These trees were comprised of 17 species of which seven are among those prominent on pine sites. From disks cut at one or more heights in each tree, Wartluft found that bark moisture content decreased as disk diameter increased, whereas wood moisture content averaged about the same in disks of all diameters (fig. 13-68).

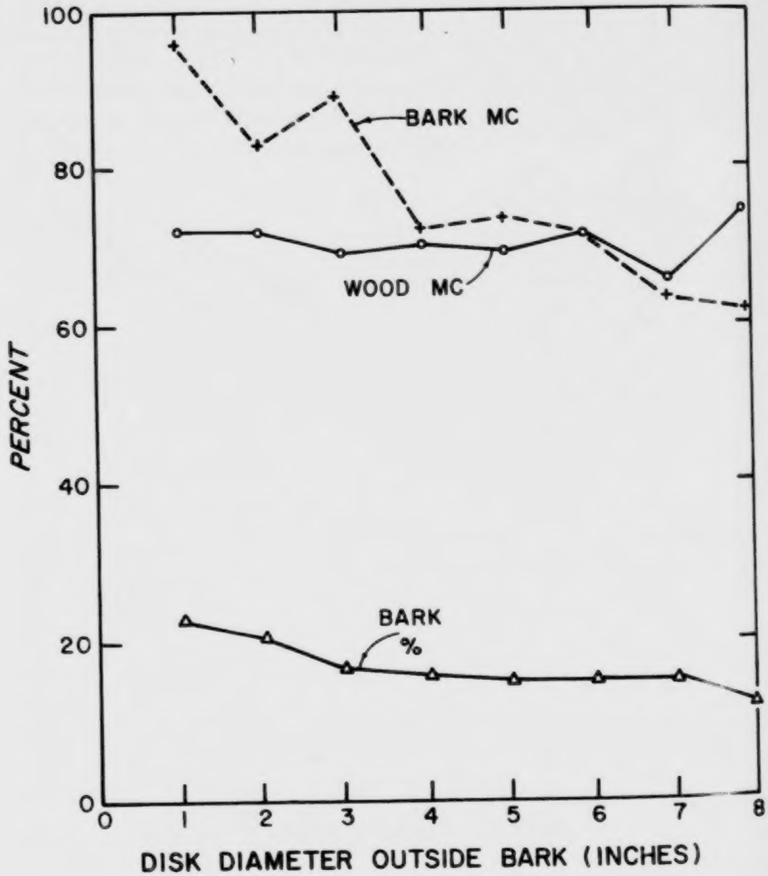

Figure 13-68.—Average bark and wood moisture content (dry-weight basis), and percentage of bark, related to diameter of disks cut throughout stems and branches from hardwoods 1 to 10 inches in dbh of 17 species growing in West Virginia. Data based on 200 trees. (Drawing after Wartluft 1977.)

Correlation with bark specific gravity.—Manwiller (1975, 1979) sampled ten 6-inch-dbh hardwoods of each of 22 hardwood species growing among southern pines across the southern range of each hardwood species, and determined the moisture content and specific gravity of their stembark and branchbark. His data (table 13-30) indicate that percentage moisture content in bark decreases as bark specific gravity increases (fig. 13-69).

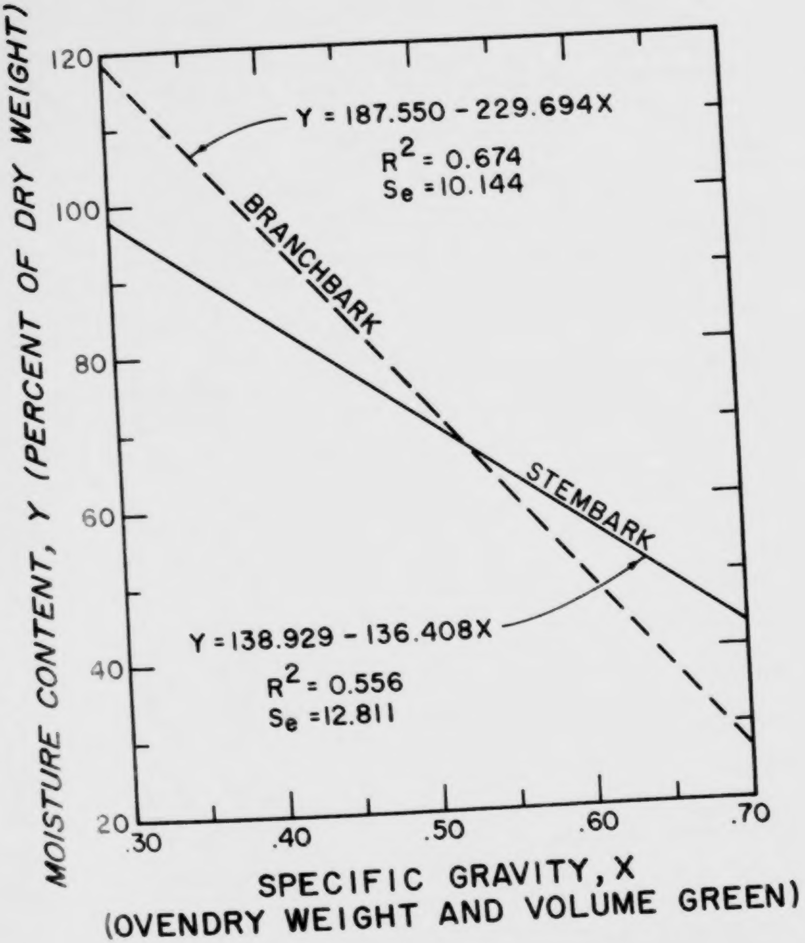

Figure 13-69.—Relation of percent moisture content when green to specific gravity in stembark and branchbark of 22 species of 6-inch hardwoods sampled Southwide from southern pine sites. The regressions are based on a 10-tree sample of each species. (Data from table 13-29.)

TABLE 13-30—*Moisture content and specific gravity (with standard deviation in parentheses) of stembark and branchbark of 6-inch hardwoods growing on southern pine sites* (derived from tables 7-7 and 8-2)[1]

Species	Moisture content		Specific gravity		
	Stem bark	Branch bark	Stem bark	Branch bark	Tree bark
	--------*Percent*---------				
Ash, green	75.9	86.0	0.407	0.450	0.411
	(8.6)	(10.2)	(.045)	(.035)	(.042)
Ash, white	68.4	77.9	.397	.460	.402
	(11.4)	(8.6)	(.040)	(.060)	(.040)
Elm, American	86.9	97.8	.395	.356	.388
	(7.7)	(6.8)	(.039)	(.034)	(.037)
Elm, winged	76.0	79.5	.341	.369	.345
	(7.8)	(7.8)	(.030)	(.031)	(.029)
Hackberry[2]	55.5	71.7	.606	.541	.596
	(6.1)	(8.7)	(.056)	(.049)	(.053)
Hickory, true	72.9	84.6	.522	.467	.516
	(10.5)	(10.8)	(.053)	(.059)	(.052)
Maple, red	74.4	89.4	.535	.469	.525
	(2.6)	(6.9)	(.027)	(.034)	(.023)
Oak, black	56.2	62.5	.612	.542	.606
	(5.4)	(4.0)	(.044)	(.042)	(.041)
Oak, blackjack	43.6	56.2	.642	.548	.631
	(6.4)	(8.9)	(.033)	(.031)	(.031)
Oak, cherrybark	54.1	68.2	.622	.520	.612
	(4.2)	(3.6)	(.052)	(.030)	(.048)
Oak, chestnut	—	—	—	—	—
Oak, laurel	57.4	76.0	.630	.521	.618
	(6.3)	(6.6)	(.043)	(.057)	(.038)
Oak, northern red	55.7	62.6	.644	.536	.636
	(14.5)	(5.6)	(.044)	(.050)	(.043)
Oak, post	48.9	65.1	.498	.438	.488
	(9.4)	(12.0)	(.055)	(.049)	(.054)
Oak, scarlet	55.6	67.0	.618	.511	.609
	(8.6)	(7.7)	(.064)	(.042)	(.060)
Oak, Shumard	52.2	66.1	.644	.540	.636
	(4.0)	(5.9)	(.062)	(.060)	(.058)
Oak, southern red	52.9	66.6	.601	.504	.593
	(8.1)	(6.1)	(.039)	(.033)	(.036)
Oak, water	54.4	73.5	.628	.508	.618
	(7.0)	(8.1)	(.052)	(.046)	(.049)

See footnotes at end of table.

TABLE 13-30—*Moisture content and specific gravity (with standard deviation in parentheses) of stembark and branchbark of 6-inch hardwoods growing on southern pine sites* (derived from tables 7-7 and 8-2)[1]—Continued

Species	Moisture content		Specific gravity		
	Stem bark	Branch bark	Stem bark	Branch bark	Tree bark
	--------*Percent*--------				
Oak, white	58.1	69.6	.543	.488	.537
	(8.5)	(8.8)	(.055)	(.027)	(.051)
Sweetbay	102.1	100.6	.440	.390	.434
	(11.6)	(13.0)	(.018)	(.045)	(.017)
Sweetgum	89.3	106.9	.369	.416	.373
	(9.9)	(8.2)	(.047)	(.038)	(.045)
Tupelo, black	69.8	88.4	.428	.433	.428
	(16.9)	(12.8)	(.051)	(.064)	(.051)
Yellow-poplar	125.8	134.4	.390	.335	.385
	(23.9)	(14.3)	(.035)	(.035)	(.031)

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[1] Each value is an average of 10 trees; see table 3-1 and 16-3 for additional tree data. Moisture contents are based on ovendry weights. Specific gravity is based on unextracted weights and green volumes.

[2] Mostly sugarberry.

Trees 1 to 10 inches in dbh.—Average bark moisture content in the small trees studied by Wartluft (1977) varied with species, as follows (ovendry-weight basis):

Species	Bark moisture content
	----*Percent*----
Hickory, sp.	54
Maple, red	69
Oak, chestnut	64
Oak, red sp.	75
Oak, white	66
Tupelo, black	89
Yellow-poplar	104

Understory trees 1.0 to 4.9 inches in dbh.—See tabulation at the beginning of this subsection 13-4.

Trees 6 inches in dbh.—Manwiller (1975) found that in 6-inch pine-site hardwoods (table 13-30) bark moisture contents were lowest in the oaks and hackberry—with means ranging from 44 to 58 percent in the stem and 56 to 76 for branch material. In the intermediate range were the ashes, winged elm, black tupelo, hickory, and red maple; in this group, moisture contents ranged from 68 to 76 percent in stembark and 80 to 89 percent in branchbark. American elm, sweetgum, and sweetbay contained significantly higher bark moisture, the range being from 87 to 102 percent in the stem and 98 to 107 percent in the branches. Yellow-poplar, with 134.4 percent in branchbark and 125.8 percent in stembark, contained more bark moisture than any other species tested.

Stembark moisture content averaged lower than that of branchbark in 19 of the 22 species; the difference ranged from 6.3 percentage points in black oak to 18.6 in laurel oak. The three species having no difference were yellow-poplar, sweetbay, and winged elm.

Sawtimber from Mississippi River bottomlands.—Schlaegel[4] provided data on bottomland sawtimber trees of three of the same species studied by Manwiller (1975); the stembark moisture contents Schlaegel observed were not greatly different from those of Manwiller's 6-inch pine-site trees, as follows:

	Stembark moisture content	
Species	Average	95 percent confidence bounds
	Percent	
Ash, green	74.0	67.9–80.1
Sugarberry	68.3	64.1–72.5
Sweetgum	87.4	80.7–94.1

Black oak.—The Tennessee Valley Authority (1972) analyzed bark moisture content of 26 black oak sawtimber trees from Tennessee, western North Carolina, and western Kentucky. They found that crownbark had higher moisture content than bark of the merchantable bole, and that bark moisture content decreased with increasing tree dbh (table 13-31).

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[4] Unpublished data (1979) from B. E. Schlaegel, U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Stoneville, Miss.

TABLE 13-31—*Moisture content of bark (ovendry weight basis) from merchantable boles and crowns of black oak sawtimber trees related to tree dbh* (Tennessee Valley Authority 1972)[1]

Dbh	Merchantable bole to an 8-inch top dib	Crown
	Percent	
12	48.4	54.7
14	46.0	52.3
16	44.0	50.6
18	42.4	48.1
20	41.7	46.6
22	40.4	45.0
24	39.5	43.6
26	39.0	42.2
28	38.0	41.1
30	37.1	39.9

[1] Data based on 26 trees sampled in Tennessee, western North Carolina, and western Kentucky. W. W. King, in personal correspondence dated August 14, 1981, advised that additional black oak trees were subsequently sampled that confirmed these moisture contents.

Northern red, scarlet, and southern red oak and yellow-poplar sawtimber.—Clark et al. (1980abc) provided data on the moisture content and specific gravity of bark and wood components of northern red oaks from western North Carolina, scarlet oak from the Tennessee Cumberland Plateau, and southern red oak from the Highland Rim in Tennessee. Clark and Schroeder (1977) provided similar data for yellow-poplar in western North Carolina. All of these data are summarized in table 13-32.

TABLE 13-32—*Average bark and wood moisture content, specific gravity, and green weight per cubic foot of four southern hardwood species of trees and tree components* (Clark et al. 1980abc; Clark and Schroeder 1977)[1]

Tree component	Average and standard deviation		
	Specific gravity	Moisture content	Green weight per cubic foot
		Percent	*Pounds*
NORTHERN RED OAK			
Wood			
Total tree	0.581 ± 0.020	80 ± 4.9	65 ± 1.5
Stem (butt to 4-inch d.i.b. top)	.574 ± .021	83 ± 5.4	65 ± 1.7
Saw log (butt to 8-inch d.i.b. top)	.568 ± .022	85 ± 5.8	66 ± 1.5
Pulpwood (8- to 4-inch d.i.b. top)	.608 ± .026	72 ± 4.7	65 ± 1.9
Branches	.605 ± .024	69 ± 4.0	64 ± 1.9
Bark			
Total tree	0.616 ± .028	63 ± 5.8	62 ± 2.0
Stem (butt to 4-inch d.i.b. top)	.631 ± .032	61 ± 6.1	63 ± 2.3
Saw log (butt to 8-inch d.i.b. top)	.634 ± .038	58 ± 6.0	63 ± 2.5
Pulpwood (8- to 4-inch d.i.b. top)	.658 ± .038	55 ± 4.8	64 ± 2.2
Branches	.589 ± .046	66 ± 9.0	61 ± 2.6
SCARLET OAK			
Wood			
Total tree	0.608 ± 0.022	76 ± 4.4	67 ± 1.5
Stem (butt to 4-inch d.i.b. top)	.595 ± .024	80 ± 5.4	67 ± 1.7
Saw log (butt to 8-inch d.i.b. top)	.592 ± .028	83 ± 5.1	68 ± 2.2
Pulpwood (8- to 4-inch d.i.b. top)	.618 ± .026	67 ± 4.8	67 ± 1.9
Topwood (4- to 2-inch d.i.b. top)	.630 ± .027	68 ± 4.8	66 ± 1.9
Branches	.648 ± .027	62 ± 3.2	66 ± 2.4
Bark			
Total tree	0.611 ± 0.027	59 ± 3.1	61 ± 2.7
Stem (butt to 4-inch d.i.b. top)	.629 ± .031	57 ± 4.0	62 ± 2.7
Saw log (butt to 8-inch d.i.b. top)	.624 ± .036	58 ± 4.6	61 ± 3.2
Pulpwood (8- to 4-inch d.i.b. top)	.643 ± .033	56 ± 3.5	63 ± 3.1
Topwood (4- to 2-inch d.i.b. top)	.629 ± .041	58 ± 5.6	62 ± 3.4
Branches	.572 ± .045	62 ± 5.9	58 ± 4.5
SOUTHERN RED OAK			
Wood			
Total tree	0.604 ± 0.021	74 ± 5.8	66 ± 1.5
Stem (butt to 4-inch d.i.b. top)	.587 ± .022	79 ± 7.0	65 ± 1.5
Saw log (butt to 8-inch d.i.b. top)	.587 ± .022	81 ± 6.6	66 ± 1.7
Pulpwood (8- to 4-inch d.i.b. top)	.602 ± .023	72 ± 4.8	65 ± 1.8
Topwood (4- to 2-inch d.i.b. top)	.633 ± .033	65 ± 3.7	65 ± 2.6
Branches	.659 ± .024	60 ± 4.2	66 ± 1.8
Bark			
Total tree	0.642 ± 0.035	47 ± 4.7	59 ± 2.6
Stem (butt to 4-inch d.i.b. top)	.652 ± .042	44 ± 3.9	58 ± 3.0
Saw log (butt to 8-inch d.i.b. top)	.651 ± .046	44 ± 4.3	58 ± 3.1
Pulpwood (8- to 4-inch d.i.b. top)	.668 ± .042	43 ± 4.0	60 ± 3.5
Topwood (4- to 2-inch d.i.b. top)	.667 ± .031	48 ± 7.0	62 ± 3.5
Branches	.606 ± .044	55 ± 5.1	58 ± 3.2

See footnotes at end of table.

TABLE 13-32—*Average bark and wood moisture content, specific gravity, and green weight per cubic foot of four southern hardwood species of trees and tree components* (Clark et al. 1980abc; Clark and Schroeder 1977)[1]—Continued

Tree component	Average and standard deviation		
	Specific gravity	Moisture content	Green weight per cubic foot
		Percent	*Pounds*
YELLOW-POPLAR			
Wood			
Total tree	0.407 ± 0.029	104 ± 13	51.8 ± 3.5
Total stem	.407 ± .030	104 ± 14	51.8 ± 3.7
Saw log section	.406 ± .029	103 ± 13	51.5 ± 3.8
Pulpwood section	.413 ± .037	103 ± 18	52.3 ± 4.6
Topwood section	.419 ± .035	111 ± 13	55.2 ± 4.4
Branches	.424 ± .026	106 ± 15	54.4 ± 3.9
Bark			
Total tree	0.325 ± 0.028	142 ± 36	49.1 ± 8.4
Total stem	.332 ± .034	126 ± 29	46.8 ± 8.4
Saw log section	.328 ± .035	124 ± 28	46.1 ± 8.0
Pulpwood section	.354 ± .027	123 ± 35	49.3 ± 8.2
Topwood section	.350 ± .035	151 ± 27	54.8 ± 6.5
Branches	.285 ± .048	247 ± 66	59.9 ± 3.1

[1] Moisture content expressed as a percent of ovendry weight. Specific gravity expressed on basis of ovendry weight and green volume.

MOISTURE CONTENT OF BARK RESIDUES

Cassens and Choong (1975) collected bark from logs at two mills near Baton Rouge, La. The logs at mill 1 were freshly yarded and end-checking had not developed; those at mill 2 had been stored longer, end-checking had developed, and bark was partially dried, as follows:

Species	Bark moisture content at	
	Mill 1	Mill 2
	Percent, ovendry weight basis	
Ash, sp.	62.7	39.9
Elm sp.	85.2	—
Oak, red sp.	64.0	45.1
Oak, white	70.5	—
Sweetgum	63.8	49.6
Tupelo sp.	80.8	74.3

Wartluft (1974a) measured bark residue moisture content from 686 sawlogs of six hardwood species groups at four sawmills in West Virginia, two with floating cutterhead debarkers and two with rosser-head debarkers. He found that the average moisture content of the bark residues differed with species, as follows:

Species	Moisture content
	Percent
Basswood (*Tilia americana* L.)	114
American beech (*Fagus grandifolia* Ehrh.)	68
Maple (*Acer sp.*)	55
Oak, chestnut and white, and hickory sp.	59
Oak, red sp.	63
Yellow-poplar	96

Unpublished 1980 data of M. S. White, Virginia Polytechnic Institute and State University, indicate that in Blacksburg, West Virginia, chip piles gain moisture content during exterior storage, as follows:

Residue types and zone in pile	Initial moisture content	After 5 months
	---*Percent of ovendry weight*--	
Hardwood whole-tree chips		
Inner zones	73	53
Outer zones	73	134
Average	73	110
Hardwood sawdust		
Inner zones	87	150
Outer zones	87	161
Average	87	155
Hardwood bark		
Inner zones	70	91
Outer zones	70	155
Average	70	130

White concluded that high piles (e.g., 20 ft high) gain less moisture during several months of storage than low piles (e.g., those 10 ft high).

See figures 20-18AB for time vs. moisture content of chips spread 4 to 12 in deep—roofed and with no roof, turned and left unturned.

Clark et al. (1974) sampled 47 yellow-poplar trees 12 to 28 inches in dbh from western North Carolina and found that stembark moisture content averaged 114 percent for sawlog portions and 102 percent for pulpwood portions. These determinations were made on laboratory-removed bark, not on bark residue removed by mill debarking equipment which normally contains some wood.

EQUILIBRIUM MOISTURE CONTENT OF BARK

See introductory text of section 8-3 for the definition of equilibrium moisture content. Martin (1967) measured the equilibrium moisture content of bark from several hardwood species, including two that commonly grow where southern pines grow (table 13-33). He found that adsorption and desorption curves for wood and bark are similar, but that black oak bark moisture contents were lower at all equilibrium conditions than those for other softwood and hardwood barks evaluated except aspen (*Populus tremuloides* Michx.). Also, at low relative humidities bark was somewhat more hygroscopic than wood.

Figure 13-70 illustrates a hysteresis loop for bark of southern hardwoods exposed to air at 25°C and up to 94 percent relative humidity. These data are specific to bark of 10 of the species in the collection described in tables 3-1 and 16-3, i.e., green ash, white ash, American elm, hickory, red maple, southern red oak, white oak, sweetbay, sweetgum, and yellow-poplar. The mean sorption data for all 22 species (table 3-1) were not significantly different from data for the 10 selected species (Okoh 1976, p. 25, 137, and 138). The curves through the data points of figure 13-70 are calculated isotherms based on the Hailwood and Horrobin (1946) model.

Okoh's (1976) data permitted computation of the ratio of adsorption moisture content to desorption moisture content at 25°C for the 10 species listed above throughout a range of relative humidities (fig. 8-10). The ratio was minimum (about 0.86) near 30 percent relative humidity and increased to 0.93 as relative humidity approached 90 percent; the ratios for wood were consistently lower than those for bark of these species.

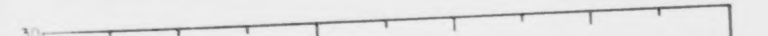

Figure 13-70.—Mean sorption isotherms for inner bark of 10 southern hardwoods at 25°C. (Drawing after Okoh 1976, p. 26; Okoh and Skaar 1980.)

Table 13-33—*Equilibrium moisture content of American elm and black oak bark at 25°C, ovendry-weight basis* (Martin 1967)

Relative humidity (percent) and condition	American elm[1]	Black oak[2]
	Percent	
19		
Adsorption	4.04	2.95
Desorption	5.95	5.23
43		
Adsorption	7.47	5.43
Desorption	9.08	7.98
75.5		
Adsorption	12.59	9.72
Desorption	14.66	11.92
86		
Adsorption	15.01	11.56
Desorption	17.20	13.42
93		
Adsorption	20.26	15.52
Desorption	23.19	18.07

[1] Based on bark from three trees.

[2] Based on bark from one tree.

HEAT OF SORPTION

When bark adsorbs water, heat is evolved. The amount of heat given off when 1 gram of ovendry bark is immersed in sufficient liquid water to bring the bark to fiber saturation is defined as the **total integrated heat of wetting.** Data specific to bark from 6-inch hardwoods grown on southern pine sites indicate that total integral heat of wetting in water at 25°C is greatest for inner bark of northern red oak (20.45 calories per gram) and least for outer bark of hackberry (11.63 calories per gram) as shown in table 8-13 from Kajita (1975).

13-5 CHEMICAL CONSTITUENTS

Major elements composing the organic portion of bark are carbon, oxygen, and hydrogen. Bark contains only small amounts of nitrogen. Significant amounts of mineral elements remain as ash when bark is burned. The **ultimate analyses** of barks of two species groups (sampled from 30 eastern Canadian mills) that grow in the southern pine region of the United States were reported by Millikin (1955) as follows:

Element	Soft maples	Soft elms
	Percent	
Carbon	50.1	46.9
Oxygen	40.7	39.1
Hydrogen	5.9	5.3
Nitrogen	.3	.6
Inorganic elements, mostly metallic, found in ash	3.0	8.1
	100.0	100.0

The carbon, oxygen, and hydrogen are combined to form the organic polymer substances that make up the bulk of bark. These polymers are of two main classes, carbohydrates and phenolics. The polymeric **carbohydrates,** also called **polysaccharides,** are made up of chains of sugar molecules. Cellulose and hemicelluloses comprise most of the polysaccharide portion of bark. Together they are called **holocellulose.**

Cellulose and hemicellulose in the fiber portion of bark are considered similar to corresponding materials in wood, although Binotto et al. (1971) found that cellulose from chestnut oak bark was less crystalline than that from wood of this species. It is extremely difficult—perhaps impossible—to isolate cellulose from bark without degrading it.

The polymeric phenolic portion of bark is, in part, a substance called **lignin.** The standard lignin analysis, however, even when applied to extractive-free bark, gives misleading results since the "lignin" product consists of a mixture of true lignin, and suberin and polyphenolic impurities. This mixture has a methoxyl content of only 8-10 percent versus 20-22 percent for true hardwood lignin (Harkin and Rowe 1971). Like the lignin from wood, hardwood bark lignins are composed of syringyl, guaiacyl, and small amounts of *p*-hydroxyphenyl nuclei. However, syringaldehyde/vanillin ratios are usually much lower in oxidation products from bark than from wood lignins. Oxidation products from bark lignins suggest a more highly condensed polymer in bark than in wood lignins (Hemingway In press).

In addition to the polymeric substances, bark also contains many low-molecular-weight **extractives** that are soluble in neutral organic solvents and water. Among bark extractives, polar materials (tannins, polyphenols, glycosides) are generally three to five times as abundant as non-polar constituents (e.g., fats, waxes, terpenes, steroids).

As noted previously, bark also contains significant quantities of inorganic substances which remain as **ash** when bark is burned. In determining ash content it is difficult to differentiate inherent inorganic materials from windborne materials lodged in the bark.

SUMMATIVE ANALYSIS

The chemical components of dry hardwood bark of pine-site hardwoods can be summed to 100 percent in **summative** or **proximate analysis;** the somewhat arbitrary percentages which follow are based on data from Harkin and Rowe (1971) for hardwood barks in general.

Component	Percent (approximate)
"Lignin"	37 to 46
Polysaccharides	30 to 42
Extractives	5 to 10
Ash	up to 20
	100

Harkin and Rowe note that the range of composition of bark is much wider than that of wood, and the high "lignin" content makes it difficult to prepare holocellulose from even well extracted bark. They suggest removing extractives with solvents, then hydrolyzing the residue with acid, and determining the monosaccharides formed by measuring their reducing power with copper salts, or as individual sugars using chromatographic and colorimetric methods.

Hergert[5] applied modern analytical methods to make summative analyses of bark from six southern hardwoods (table 13-34). Bolts of trees 25 to 40 years old and 8 to 14 inches in dbh were sampled in the vicinity of Jesup (southeast) Georgia and Watts Bar (eastern) Tennessee. The number of trees sampled per species varied, but each value in table 13-34 is based on several trees.

Chang and Mitchell (1955) reported total percentage of reducing sugars obtained after H_2SO_4 hydrolysis of unextracted bark and bark extracted with neutral solvents or NaOH, as follows:

Species	Solvent		
	None	Neutral	NaOH
	Percent of unextracted bark weight, dry basis		
Elm, American	37.0	35.4	27.0
Oak, northern red	32.4	31.7	28.3
Oak, white	27.8	28.2	21.2
Sweetgum	35.6	33.5	26.4
Tupelo, black	29.6	27.2	22.4

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[5] Hergert, H. L. Chemical constituents of bark from southeastern hardwoods. Unpublished data privately communicated to the author December 12, 1977.

TABLE 13-34—*Summative chemical analyses and corrected carbohydrate analyses of bark from six southeastern hardwoods* (Hergert, H. L., see text footnote 5)

Component	Hickory sp.	Oak, water	Oak, willow[1]	Redbay[2]	Sweetgum	Tupelo sp.
	Percent					
SUMMATIVE ANALYSES						
Extractives						
Wax	1.61	2.01	2.10	1.70	1.30	2.12
Phenols	2.15	.38	.76	3.75	.14	.09
Tannins and sugar	10.71	11.49	6.41	22.70	3.31	6.45
Polymeric carbohydrates	3.85	3.78	5.30	3.36	6.94	8.39
Cellulose	18.4	15.8	17.1	20.0	21.5	15.5
Hemicelluloses						
Glucomannan	.9	.6	.5	.9	1.3	.8
Acetylglucuronoxylan	8.3	21.1	21.1	11.0	15.3	12.7
Arabinogalactan	4.2	2.4	2.4	4.3	3.8	4.0
Pectin	4.3	3.4	3.7	3.0	6.9	6.9
Lignin	17.6	21.7	18.3	17.5	22.8	21.1
Phenolic acid	23.1	14.9	19.8	9.5	9.8	12.5
Ash	4.9	2.4	2.6	2.3	7.0	9.5
	100.0	100.0	100.1	100.0	100.1	100.0
CARBOHYDRATE CONTENT CORRECTED FOR INCOMPLETE HYDROLYSIS						
Xylan	7.6	19.1	18.2	11.8	13.5	11.5
Mannan	.8	.4	.4	.8	1.0	.6
Glucan	22.9	19.4	20.2	29.6	24.8	19.0
Galactan	1.6	1.3	1.4	2.8	1.3	1.9
Arabinan	3.4	1.6	1.4	3.6	3.0	2.9

[1] *Quercus phellos* L.

[2] *Persia borbonia* (L.) Spreng.

Hexose and pentose sugar contents of three of these species are shown in table 13-35. For example, the total carbohydrate content of white oak (neutral-solvent extracted) was 28.2 percent, of which 16.9 percent was glucan, 1.1 percent galactan, 0.6 percent mannan, 6.8 percent xylan, and 2.0 percent arabinan; 0.8 percent was unidentified carbohydrate—probably because of incompletely hydrolyzed material.

EXTRACTIVES

The chemistry of extractives of bark of pine-site hardwoods is complex. Section 6-6 summarizes the literature. Readers needing additional information should consult Rowe and Connor (1979) and Hemingway (1981; In press).

TABLE 13-35—*Reducing sugars in barks of three southern hardwoods obtained after neutral extraction and hydrolysis* (Chang and Mitchell 1955)

Sugars	Oak, northern red	Oak, white	Sweetgum
	- Percent of unextracted bark weight, dry basis-		
Hexosan			
Mannan	0.3	0.6	1.0
Glucan	16.8	16.9	20.1
Galactan	1.0	1.1	1.0
Pentosan			
Xylan	11.1	6.8	6.7
Arabinan	1.9	2.0	3.7
Unidentified carbohydrate	.6	.8	1.0

The percentage of extractives varies with species and extraction procedure. F. G. Manwiller found (table 6-14) that when ground bark of small pine-site hardwoods was extracted with alcohol-benzene solution followed by a final extraction with ethanol, stembark extractives varied from a low of 7.97 percent in hackberry to 18.45 percent in yellow-poplar; stembark of the 22 species he studied had average extractive content of 14.41 percent. Branchbark averaged higher in extractives content (16.65 percent) than stembark. Both green and white ash had branchbark extractives content greater than 20 percent (table 6-14).

Murphey et al. (1970) determined extractives content of stembark from species of hardwoods commonly found in the South, using four solvents plus hot and cold water. He found that white ash bark varied from 10.7 to 15.0 percent extractives, American elm from 10.9 to 17.3 percent, red maple from 9.2 to 16.4 percent, and white oak from 8.2 to 15.4 percent depending on the solvent (table 13-36). The four solvents used individually each extracted roughly the same percentages from four hardwood barks sampled (table 13-36). Applied successively by Chang and Mitchell (1955) to five hardwood species, the same solvents extracted amounts totalling about the same as that extracted by 1-percent sodium hydroxide alone (table 13-37A).

Choong and Fogg (1976) reported the following extractives contents from stembark of four sweetgum trees sampled in eastern Louisiana—two from a bottomland site along the Mississippi River and two from an upland site (based on unextracted ovendry weight):

Solvent	Average	Standard deviation
	Percent	
Ether	1.88	0.86
Ethanol	2.88	1.32
Hot water	9.05	1.24

Sandala et al. (1981) found that inner bark of both white ash and northern red oak produced more extractives than outer bark when extracted successively with diethyl ether, alcohol-benzene, cold water, and hot water (table 13-37B).

TABLE 13-36—*Extractives content by five solvents from stembark of four hardwood species sampled in Pennsylvania* (Murphey et al. 1970)

Solvent[1]	Ash, white	Elm, American	Maple red	Oak, white
	---Percentage of unextracted ovendry weight --			
Acetone	12.2	14.2	13.0	10.0
Ethanol	10.7	10.9	16.4	14.2
Ethanol-benzene	13.2	14.9	13.1	9.8
1-percent NaOH	15.0	17.3	16.3	14.5
Hot water	12.9	14.9	16.0	15.4
Cold water	11.2	12.3	9.2	8.2

[1] Applied individually, not successively.

TABLE 13-37A—*Percentage of weight of unextracted bark (ovendry-weight basis) of five hardwood species soluble in successive extractions with benzene, alcohol, hot water, and 1-percent sodium hydroxide; or with 1-percent sodium hydroxide only* (Chang and Mitchell 1955)

Species	Soluble in successive extractions with				Solubility of original bark in 1-percent sodium hydroxide
	Benzene	Alcohol	Hot water	1-percent sodium hydroxide	
	Percent				
Elm, American	0.5	10.1	6.0	27.0	45.2
Oak, northern red	4.8	7.9	3.6	22.3	39.8
Oak, white	2.7	4.4	5.8	26.5	38.2
Sweetgum	1.5	17.7	7.4	21.3	48.3
Tupelo, black	2.5	4.6	5.3	27.8	39.4

TABLE 13-37B—*Percentage of weight of unextracted inner and outer bark of white and northern red oak (ovendry-weight basis) soluble in successive extractions with four neutral solvents* (Sandala et al. 1981)[1]

Species and bark portion	Diethyl ether	Alcohol benzene	Cold water	Hot water	Total
	Percent				
Oak, northern red					
Inner bark	4.98	7.94	5.45	2.53	20.90
Outer bark	5.34	3.35	4.12	2.44	15.25
Oak, white					
Inner bark	.63	4.86	3.79	2.73	12.01
Outer bark	1.69	3.57	2.23	2.94	10.43

[1] Each value is the average based on three bark specimens collected in Pennsylvania from sawlogs, ground to pass a 45-mesh screen and be retained on a 60-mesh screen, and ovendried.

Within-tree and seasonal variations.—Binotto and Murphey (1975) observed little variation in percent extractives with height in chestnut oak trees, but found that inner bark consistently had greater extractives content than rhytidome. The extractives content of the rhytidome was stable throughout the year, but that of inner bark increased slightly in the spring and decreased in the summer.

Tannin content.—Tannin content of barks of hardwoods found where southern pines grow is generally less than 12 percent (tables 13-38A and 13-38B). The chemistry of the tannins from most of these tree barks is largely unknown.

Other extractives.—See sec. 6-6.

TABLE 13-38A—*Tannin content of stembark from southern hardwoods commonly found where southern pines grow*

Species	Tannin content	Reference
	Percent	
Ash, green	Insignificant	1
Ash, white	Insignificant–4.8	1
Elm, American	2.8-5.6	2
	Insignificant	1
Elm, winged	Insignificant	1
Hackberry	Insignificant	1
Hickory		
Bitternut	7.8	3
Mockernut	Insignificant	3
Pecan	5.7	3
Pignut	7.6-10.0	3
Sand	6.7	3
Shagbark	Insignificant	3
Shellbark	4.7	3
Maple, red	6.9	1
Oak, black	5.6-12.0	1
Oak, blackjack	7.7-9.2	1
Oak, cherrybark	—	—
Oak, chestnut	6.3-12.0	1
Oak, laurel	—	—
Oak, northern red	2.2-10.9	2
	4.6-11.1	1
Oak, post	2.3-9.4	1
Oak, scarlet	6.6-7.7	1
Oak, Shumard	4.3-5.2	1
Oak, southern red	6.4-10.0	1
Oak, water	4.3-8.0	1
Oak, white	2.8-7.9	2
Sweetbay	Insignificant	1
Sweetgum	Insignificant–10.2	2
	7.6	1
Tupelo, black	Insignificant–1.7	2
Yellow-poplar	Insignificant	1

[1] Rowe and Conner (1979).
[2] Chang and Mitchell (1955).
[3] Mitchell (1955).

TABLE 13-38B—*Total tannin content found in stembark of 11 southern hardwoods*[1,2]

Species	Tannin content
	Percent
Ash, green	4.2
Elm, winged	10.0
Hickory, mockernut	11.7
Maple, red	7.9
Oak, blackjack	9.5
Oak, post	6.9
Oak, southern red	11.2
Oak, white	5.2
Sweetbay	1.1
Sweetgum	6.1
Tupelo, black	1.4

[1] Private communication from H. A. Schroeder based on his progress report for October 1, 1978 through December 31, 1978 on Forest Service, U.S. Department of Agriculture Cooperative Agreement 12-111 (Colorado State University reference no. 31-1470-2006).

[2] Data based on bark of a few small trees of each species sampled among southern pines in Louisiana. Tannin content computed by multiplying Stiasny value and percent solubility in ethanol and hot water.

INORGANIC COMPONENTS

The significance of inorganic components in trees, and methods for their determination are discussed in the introduction to section 6-7. Bark has a higher content of inorganic components than wood, partly due to minerals present in native bark but also due to windblown soil and sand lodged in bark crevices and fissures.

Ash content.—Data on ash content of bark from 6-inch-diameter, pine-site hardwoods of 22 species sampled throughout their southern ranges (table 6-18) indicated averages and among-species ranges as follows:

Statistic and species	Stembark	Branchbark
	Percent of unextracted ovendry weight	
Average (22 species)	7.87	6.76
Minimum (yellow-poplar)	4.08	4.12
Maximum (winged elm)	12.12	11.75

Chang and Mitchell (1955) found ash contents as follows in species sampled in Illinois, but also common in the South (percent of unextracted ovendry weight):

Species	Ash content
	Percent of unextracted ovendry weight
Elm, American	9.5
Oak, northern red	5.4
Oak, white	10.7
Sweetgum	5.7
Tupelo, black	7.2

Choong et al. (1976) determined ash content of bark sampled from 10 logs each of sweetgum, red oak sp., and ash sp. cut from the Mississippi Delta near Baton Rouge, La. They found that outer bark ash content was 8.9 percent in red oak, 10.4 percent in sweetgum, and 12.3 percent in white and green ash. Inner bark ash content was greater in red oak (11.1 percent) and sweetgum (12.8 percent) than in outer bark; in ash, however, inner bark ash content (12.1 percent) was about the same as for outer bark. By their procedure, samples were treated with nitric acid before ashing and results were expressed as percent of unextracted ovendry bark weight.

In a similar experiment based on two upland and two bottomland sweetgum trees measuring 20 inches in dbh sampled near Baton Rouge, Choong et al. (1974) found that stembark of the four trees varied considerably in ash content, ranging from 7.1 percent in one upland tree to 10.7 percent in one bottomland tree.

Table 13-34 indicates a broad range in ash content of bark among six southeastern hardwood species groups—from 2.3 percent in redbay to 9.5 percent in tupelo sp.

Mineral content.—Bark mineral analyses shown in table 6-19 indicate that among-species variations in 6-inch pine-site hardwoods are significant, as follows:

Element and tissue	Minimum	Maximum
	Parts/million of ovendry weight	
Fe		
Branchbark	76 scarlet oak	243 post oak
Stembark	76 white oak	412 hackberry
Zn		
Branchbark	15 blackjack oak	195 white oak
Stembark	10 blackjack oak	157 white oak
Cu		
Branchbark	2 scarlet oak	66 green ash
Stembark	3 scarlet oak	73 green ash
Mn		
Branchbark	75 hackberry	1,136 black tupelo
Stembark	96 black oak	1,302 hickory
Na		
Branchbark	140 Shumard oak	2,758 laurel oak
Stembark	148 Shumard oak	2,762 laurel oak
Mg		
Branchbark	613 blackjack oak	2,096 hickory sp.
Stembark	491 blackjack oak	2,247 white ash
Ca		
Branchbark	6,656 sweetbay	50,975 hackberry
Stembark	6,933 sweetbay	52,420 post oak
K		
Branchbark	1,021 scarlet oak	5,456 American elm
Stembark	376 scarlet oak	4,874 American elm
Al		
Branchbark	52 white ash	308 post oak
Stembark	67 red maple	604 hackberry
P		
Branchbark	294 blackjack oak	863 American elm
Stembark	165 blackjack oak	610 American elm

Variation in mineral content between stembark and branchbark can be considerable, as follows (averages derived from table 6-19):

Element	Stembark	Branchbark
	Parts/million of ovendry weight	
Fe	135.4	120.5
Zn	34.6	41.7
Cu	13.0	12.4
Mn	567.8	596.1
Na	449.4	433.2
Mg	1,099.6	1,232.4
Ca	30,529.8	26,377.3
K	2,046.3	2,452.0
Al	174.7	146.0
P	344.4	498.8

Choong et al. (1976) sampled inner and outer bark of ten logs each of red oak (*Quercus* sp.), ash (*Fraxinus* sp.), and sweetgum cut near Plaquemine, La.; mineral contents are shown in table 13-39.

TABLE 13-39—*Mineral contents of inner and outer bark of three hardwoods sampled near Plaquemine, La.* (Choong et al. 1976)[1]

Element	Ash sp.		Red oak sp.		Sweetgum	
	Inner	Outer	Inner	Outer	Inner	Outer
			Parts/million			
Na	109.0 (21.5)	94.7 (22.5)	120.4 (31.2)	100.0 (26.0)	214.0 (29.1)	145.0 (21.3)
K	6,120.0 (25.7)	2,344.4 (41.7)	1,170.0 (32.6)	1,122.0 (12.0)	2,465.6 (52.4)	656.0 (53.0)
Ca	39,100.9 (7.9)	39,444.4 (26.4)	43,105.0 (15.8)	29,950.0 (22.2)	42,211.1 (26.2)	29,980.0 (44.8)
Mg	1,334.0 (15.0)	1,344.4 (34.0)	564.0 (74.0)	840.5 (40.0)	1,141.5 (62.2)	628.1 (14.6)
Mn	—	—	156.0 (37.0)	316.6 (45.3)	102.8 (68.5)	122.3 (89.0)
Zn	189.0 (30.0)	218.3 (33.7)	31.8 (51.4)	28.7 (59.5)	76.0 (29.8)	59.0 (42.4)
P	575.6 (30.2)	197.0 (36.0)	229.5 (26.6)	175.0 (16.7)	360.3 (27.2)	160.7 (31.4)

[1] Each value is average for 10 sawlogs, parts/million; values in parentheses are coefficients of variation, percent.

Sulfur content of bark.—There are no published data on the sulfur content of bark from individual species of southern hardwoods. The National Council of the Paper Industry for Air and Stream Improvement, Inc. (1978) sampled sulfur content of bark fuel at four pulpmills in the Southeast (Alabama, Georgia, and Florida) and found contents of 0.010, 0.060, 0.068, and 0.134 percent; although most of the bark was from southern pines, substantial amounts of hardwood bark were also in the mixtures. It was found that just over 5 percent of the sulfur contained in bark was emitted from the mill boilers as SO_2, i.e., about 0.0001 to 0.0020 pound of SO_2 per million Btu in the bark fed to the boilers. (Stembark of small pine-site hardwoods has a heat of combustion—higher heating value—of about 7,593 Btu/ovendry pound.)

BARK pH

Bark of southern hardwoods varies considerably in acidity (or alkalinity) as measured by pH, i.e., the logarithm of the reciprocal of the hydrogen ion concentration, expressed in gram atoms per liter of a solution. pH 7 (0.0000001 gram atom of hydrogen ion per liter), the value for pure water, is regarded as neutral. pH values from 0 to 7 indicate acidity, and those from 7 to 14 alkalinity.

F. G. Manwiller, using the method of Moore and Johnson (1967), found that stembark of small pine-site hardwoods of 22 species averaged 5.23 in pH, while that of branchbark averaged 5.16 (table 6-23). Scarlet oak had lowest pH—4.70 in stembark and 4.82 in branchbark. Maximum stembark pH was observed in American elm (5.64) and maximum branchbark pH in hackberry (5.75).

Chow (1973) concluded that hot-water extraction of oak bark yielded slightly lower pH values for the extract than cold-water extraction, as follows:

Extraction by	Red oak sp.	White oak
	pH	
Hot water	4.72	5.13
Cold water	4.87	5.25

Murphey et al. (1970) found that pH of cold-water extractives from stembark of four species sampled in Pennsylvania, but common in the South, varied from 4.9 to 6.0 as follows:

Species	pH
Ash, white	6.0
Elm, American	6.0
Maple, red	4.9
Oak, white	5.5

13-6 PHYSICAL AND MECHANICAL PROPERTIES

Bark of pine-site hardwoods varies greatly in density, and is less strong than woods of the species. Volumetric shrinkage when dried may be about the same as that of wood, but varies among species. The thermal conductivity of bark is lower, and the heat of combustion higher, than that of wood.

SPECIFIC GRAVITY

Specific gravity and density are defined in the introduction to chapter 7 and by equations 7-1 through 7-4. Densities, related to specific gravity and moisture content, are tabulated for easy reference in table 7-1. Specific gravity and density of bark are affected by length and diameter of cells, thickness of cell walls, proportions of tissue types, amount of polysaccharides and lignin, extractives and inorganic constituents.

Choong and Fogg (1976) determined cell-wall density of unextracted sweetgum bark fibers using the picnometric method with water as the displacement fluid; they found that bark fiber cell-wall density averaged 1.506, slightly less than their values for sweetgum sapwood fibers (1.534) or heartwood fibers (1.553).

Specific gravity of bark, whether it is inner bark, outer bark, or whole bark, is most frequently determined from unextracted ovendry weight and green volume, the latter obtained by water immersion after saturation.

Variation among species in 6-inch trees.—In this manner Manwiller (1979) measured specific gravity of stembark and branchbark in 6-inch trees of 22 hardwood species (10 trees of each species) sampled among southern pines across the southern range of each species; tree characteristics are described in tables 3-1 and 6-3. He found (table 13-30) that stembark of winged elm and sweetgum had the lowest specific gravity (0.34 and 0.37). Yellow-poplar, American elm, the ashes, black tupelo, and sweetbay were next with values from 0.39 to 0.44. In an intermediate position were hickory, red maple, post oak, and white oak, ranging from 0.49 to 0.54. The nine red oaks and hackberry stembarks were densest with an average specific gravity of 0.62. Weight per cubic foot of green stembark (in place) ranged from 37.5 (winged elm) to 62.6 pounds in northern red oak (table 13-40).

In these small trees, yellow-poplar branchbark was least dense with specific gravity of 0.34 followed by the two elms averaging 0.36 and by sweetbay and sweetgum averaging 0.40. Intermediate were black tupelo, post oak, the ashes, hickory, and red maple, ranging from 0.43 to 0.47, averaging 0.45. The oaks and hackberry ranging from 0.49 to 0.55 were densest with an average specific gravity of 0.52. Weights per cubic foot of green branchbark (in place) varied from 41.4 (winged elm) to 58.0 pounds in hackberry (table 13-40).

TABLE 13-40—*Density of stembark and branchbark (in place) of freshly felled 6-inch hardwoods growing on southern pine sites* (Manwiller 1979)[1,2]

Species	Stembark	Branchbark
	-----Pounds per cubic foot-----	
Ash, green	44.7	52.2
Ash, white	41.7	51.1
Elm, American	46.1	44.0
Elm, winged	37.5	41.4
Hackberry	58.8	58.0
Hickory, true	56.3	53.8
Maple, red	58.2	55.4
Oak, black	59.7	55.0
Oak, blackjack	57.6	53.4
Oak, cherrybark	59.8	54.6
Oak, chestnut	—	—
Oak, laurel	61.9	57.2
Oak, northern red	62.6	54.4
Oak, post	46.3	45.1
Oak, scarlet	60.0	53.3
Oak, Shumard	61.2	56.0
Oak, southern red	57.4	52.4
Oak, water	60.5	55.0
Oak, white	53.6	51.7
Sweetbay	55.5	48.8
Sweetgum	43.6	53.7
Tupelo, black	45.4	50.9
Yellow-poplar	55.0	49.0

[1] Values tabulated are tree averages based on a sample of 10 trees (6-inch dbh) per species drawn from pine sites throughout the southern range of each species.

[2] See table 7-2 for densities of stemwood, branchwood, and tree with bark.

Variation among species in understory trees 1.0 to 4.9 inches in dbh.—Unpublished data provided September 2, 1981 by D. R. Phillips, U.S. Dep. Agric., For. Serv., Southeastern For. Exp. Stn., Clemson, S.C., compared wood and bark specific gravity of understory hardwoods (seven species) 1.0 to 4.9 inches in dbh sampled in the Piedmont of South Carolina, as follows (based on ovendry weight and green volume):

Species and component	Bark	Wood
Hickory sp.		
Stem	0.581	0.670
Branch	.479	.623
Whole tree above ground	.568	.664
Maple, red		
Stem	.569	.510
Branch	.463	.480
Whole tree above ground	.545	.503
Oak, post		
Stem	.416	.652
Branch	.449	.607
Whole tree above ground	.419	.647
Oak, southern red		
Stem	.591	.624
Branch	.505	.620
Whole tree above ground	.580	.624
Oak, white		
Stem	.476	.654
Branch	.441	.621
Whole tree above ground	.471	.650
Sweetgum		
Stem	.316	.448
Branch	.389	.460
Whole tree above ground	.326	.451
Yellow-poplar		
Stem	.386	.403
Branch	.354	.401
Whole tree above ground	.381	.402

See opening paragraphs of section 13-4 for moisture contents of these trees.

Variation among species in sawtimber.—Clark et al. (1980abc) and Clark and Schroeder (1977) provided data on specific gravity and density (in place) of bark of northern red oaks from western North Carolina, scarlet oak from the Tennessee Cumberland Plateau, southern red oak from the Highland Rim in Tennessee, and yellow-poplar in western North Carolina; these data are summarized in table 13-32.

Phillips et al. (1974) sampled bark specific gravity from sawlogs cut from 40 black oak trees selected from a mature, uneven-aged stand of mixed oaks on an upland slope in western North Carolina; they found that bark specific gravity averaged 0.55, basis of green volume and unextracted ovendry weight.

Schlaegel[4] provided data on Mississippi bottomland sawtimber trees of three of the same species studied by Manwiller, as follows (based on ovendry weight and green volume);

Species	Stembark specific gravity	
	Average	95-percent confidence bounds
Ash, green	0.487	0.471-.503
Sugarberry	.639	.621-.657
Sweetgum	.440	.422-.458

Choong and Cassens (1976a) measured specific gravity (ovendry volume and weight basis) of sawlogs of six species cut on the Mississippi River Delta and sampled from two Louisiana sawmills; they found that species specific gravity varied between mills as well as among species (table 13-41).

Martin and Crist (1968) measured stembark specific gravities, based on ovendry weight and air-dry volume, by immersion in mercury, as follows:

Species	Source	Phloem	Rhytidome
Ash, green	Georgia	—	0.243-.443
Elm, American	Michigan	—	.350-.533
Maple, red	Virginia	0.799- .918	—
Oak, black	Michigan	.793–1.046	.895-.917
Oak, chestnut	Virginia	.808– .882	.374-.712
Oak, northern red	Michigan	—	.636-.761
Oak, white	Michigan	.880- .867	—
Oak, white	Virginia	—	.622-.820
Sweetgum	Georgia	—	—.757
Yellow poplar	Virginia	.986–1.291	.309-.531

Murphey et al. (1970) measured specific gravity of bark from sawlogs sampled in Pennsylvania, with results as follows (basis of ovendry volume and weight):

Species	Specific gravity
Ash, white	0.484
Elm, American	.667
Maple, red	.805
Oak, white	.841

TABLE 13-41—*Properties of bark from sawlogs of six hardwood species cut on the Mississippi River Delta and sampled at two Louisiana sawmills* (Cassens and Choong 1976)[1]

Mill location and species	Specific gravity[2]	Moisture content[3]	Thickness[4]	Void volume[5]
		Percent	*Inch*	*Percent*
Plaquemine, La.				
Ash sp.	0.650	62.7	0.38	21.9
	(.04)	(7.2)	(.07)	(9.5)
Elm sp.	.755	85.2	.36	25.1
	(.08)	(14.2)	(.06)	(3.8)
Oak, red sp.	.858	64.0	.41	20.3
	(.04)	(21.6)	(.05)	(4.8)
Oak, white sp.	.589	70.7	.42	22.9
	(.04)	(13.4)	(.09)	(4.7)
Sweetgum	.601	63.8	.35	30.5
	(.07)	(9.6)	(.15)	(4.3)
Tupelo sp.	.503	88.5	.35	20.9
	(.04)	(18.3)	(.05)	(9.1)
Alexandria, La.				
Ash sp.	.663	39.9	.54	13.5
	(.04)	(8.7)	(.10)	(4.4)
Oak, red sp.	.901	45.1	.53	11.1
	(.04)	(11.1)	(.15)	(3.2)
Sweetgum	.617	49.6	.44	23.7
	(.06)	(9.2)	(.11)	(5.7)
Tupelo sp.	.514	74.3	.40	18.2
	(.03)	(18.1)	(.09)	(5.9)

---

[1] The first value given is average for 9 to 22 logs of each species at each location, measuring 12 to 19 inches in diameter inside bark. The second value given (in parentheses) is the standard deviation.

[2] Basis of ovendry volume and weight.

[3] Percent of ovendry weight.

[4] Single-bark thickness, averaged from four locations of maximum thickness.

[5] Void volumes determined by tracing solid and void bark areas from cross sections onto paper.

Among-tree variation.—The standard deviations in stembark and branchbark specific gravities shown in table 13-30 and the ranges shown in table 13-32 indicate that among-tree variations within a species are substantial. The variations evident in other published data also suggest variability within species related to site or geographic location.

Koch (1970), in a study of red maple trees from West Virginia, found that below 10-foot height stembark specific gravity did not vary with dbh among trees; at all heights above 10 feet, however, bark from trees 12 to 14 inches in dbh had significantly higher specific gravity than that from trees 8 to 10 inches in dbh. He also studied variation in specific gravity of stembark of yellow-poplar from West Virginia and found that at lower stem heights bark specific gravity increased slightly from the 4- to 6-inch dbh class to the 6- to 8-inch class, remaining practically constant through the 12- to 14-inch class, and then decreasing slightly in the 14- to 16-inch class; at stem heights above 16 feet, the effect of increasing dbh on bark specific gravity was very small. In scarlet, black, and northern red oaks Koch (1970) found that bark specific gravity increases through the smaller dbh classes and then decreases.

Within-tree variation.—Specific gravity of bark varies from inner bark (phloem) to outer bark (rhytidome). Koch (1971a), in a study of yellow-poplar and northern red oak trees measuring 14 to 16 inches in dbh sampled in northern West Virginia, found that inner bark of these species has significantly lower specific gravity than outer bark (fig. 13-71). In both of these species, specific gravity of both inner and outer bark tended to increase with height in tree.

Patterns of stembark variation in specific gravity with height above ground are complex. In 6-inch pine-site hardwoods Manwiller (1979) found that stembark specific gravity generally increased with height in ashes and in black tupelo and sweetgum (after an initial decrease) while in other species it decreased or remained nearly constant (fig. 13-72). In yellow-poplar trees 9.5 to 10.5 inches in dbh, Schroeder and Phillips (1973) observed highest specific gravity in upper stem sections and lowest near ground level (fig. 7-31).

In red maple trees 4 to 14 inches in dbh, Koch (1970) found that stembark specific gravity was significantly less at stump height than at breast height in all diameter classes; above 10 feet, however, the effect of height on bark specific gravity was negligible

In scarlet, black, and northern red oaks 8 to 10 inches in dbh sampled in West Virginia, Koch (1970) found that stembark increased in specific gravity from ground level to 10 to 28 feet height, and then decreased (fig. 13-73).

There are significant differences in specific gravity of stembark and branchbark that depend on species and tree size. In 6-inch pine-site hardwoods, Manwiller (1979) found that in all 11 oaks studied, yellow-poplar, sweetbay, hickory, red maple, American elm, and hackberry, stembark was denser. In sweetgum, the two ashes, and winged elm, branchbark was denser. In black tupelo there was no difference in density between stembark and branchbark (table 13-30). For further comparisons of the specific gravity of branchbark and stembark, see also the tabulation in this section under the paragraph heading *Variation among species in understory trees 1.0 to 4.9 inches in dbh.*

Table 13-32 gives the specific gravity of bark of important tree components (sawlogs, pulpwood, topwood, branches) of northern red oak from western North Carolina, scarlet oak from the Tennessee Cumberland Plateau, southern red oak from the Highland Rim in Tennessee, and yellow-poplar from western North Carolina as determined by Clark et al. (1980abc) and Clark and Schroeder (1977).

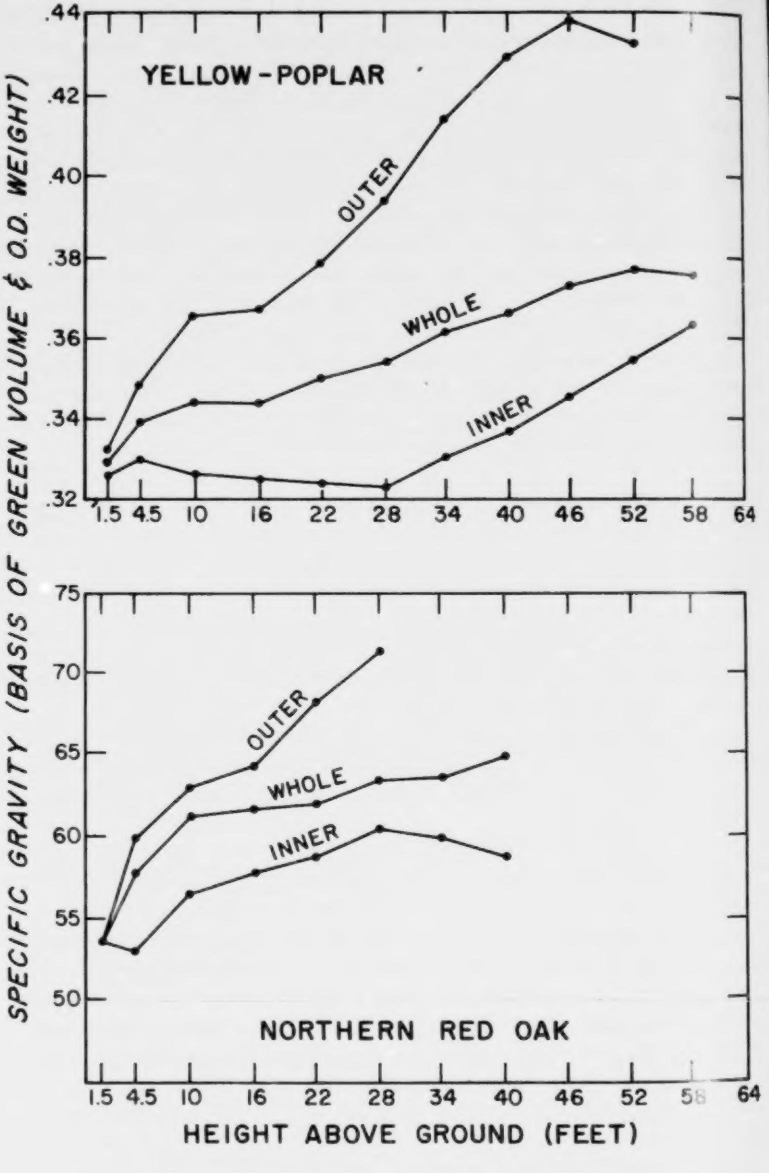

Figure 13-71.—Variation in specific gravity of unextracted inner and outer stembark with height above ground in trees 14 to 16 inches in dbh. (Top) Yellow-poplar. (Bottom) Northern red oak. (Drawing after Koch 1971a.)

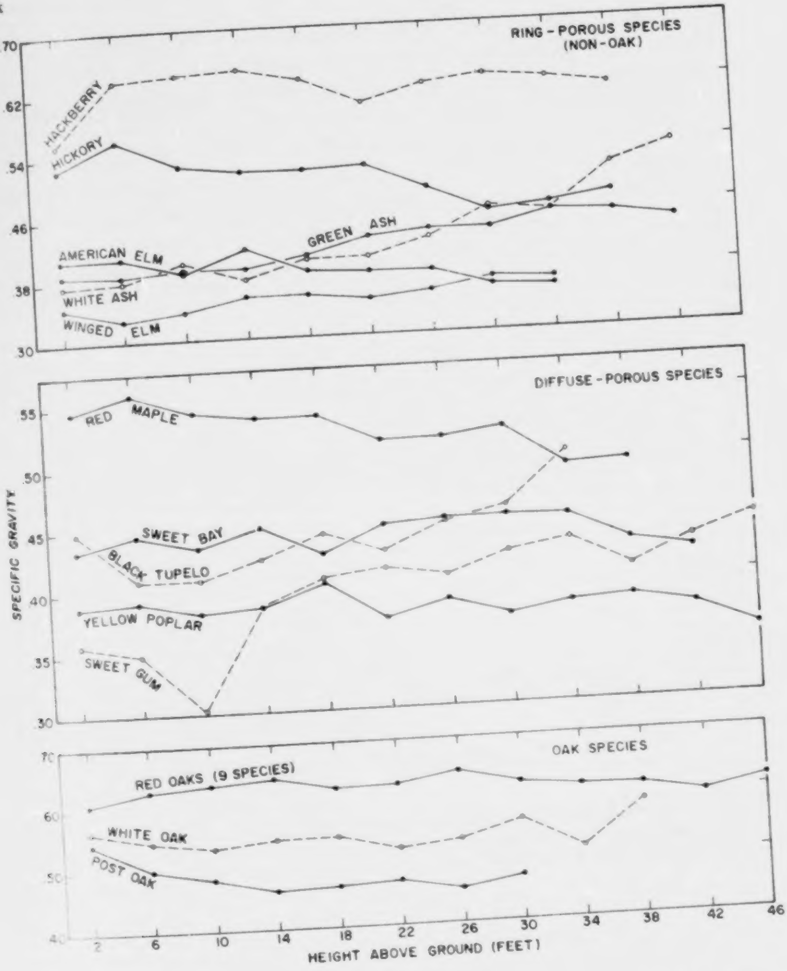

Figure 13-72.—Relationship between stembark specific gravity and height above ground in 6-inch-dbh hardwoods growing among southern pines. The red oak plot is based on data from 90 trees; the other plots represent data from 10 trees each. (Drawing after Manwiller 1979.)

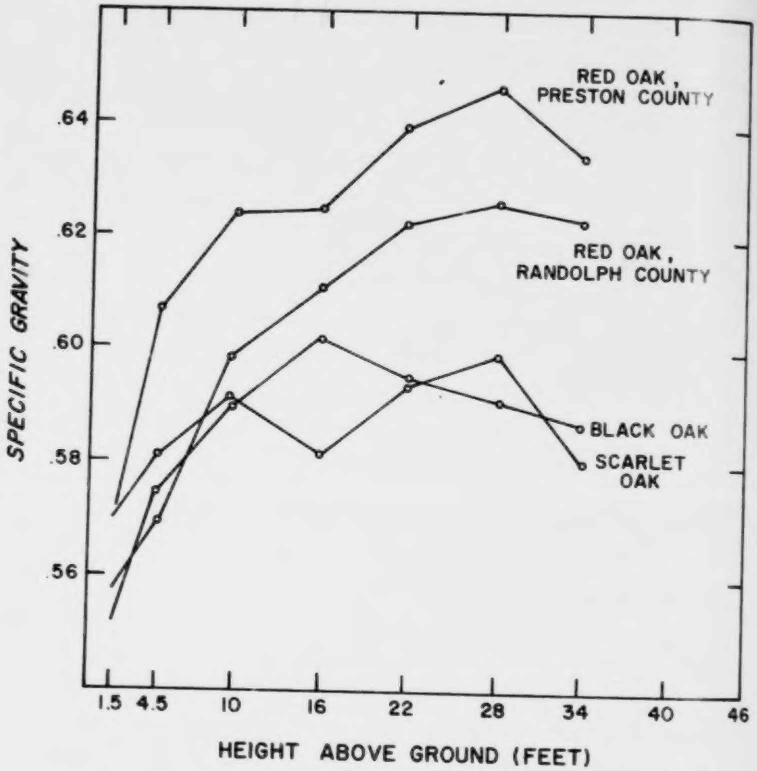

Figure 13-73.—Relationship between stembark specific gravity (basis of green volume and unextracted ovendry weight) and height above ground in three species of West Virginia oaks 8 to 10 inches in dbh. (Drawing after Koch 1970.)

Clark et al. (1974) found from a study of 47 yellow-poplar sawtimber trees in western North Carolina that stembark specific gravity (basis of green volume and unextracted ovendry weight) averaged 0.308, 0.347, and 0.343 respectively, for sawlog, pulpwood, and topwood portions of the stems. The trees averaged 19.3 inches in dbh and ranged from 11.7 to 28.4 inches.

Clark (1976) observed from 230 sawlogs cut from these yellow-poplar trees that average bark specific gravity was 0.316 and that the specific gravity of bark on the logs decreased with increased log scaling diameter.

Bulk density of bark residue.—Bark in place on a living tree or on freshly cut stems has weight per cubic foot as described in tables 13-32 and 13-39. The bulk density of piled bark residue, as it comes from mill debarkers, is also important to its use as an industrial raw material.

Vidrine and Woodson[6] studied bulk densities of green and airdry bark residue from red maple, sweetgum, yellow-poplar, oak sp., and hickory sp. collected in northern Louisiana. Bark particles obtained from debarkers (including drum debarkers) range from 2 feet in length to pulverized dust. In their evaluations of 31-cubic-foot samples (table 13-42) bulk density was highest (30.2 lb/cu ft) for green oak bark from a ring-type debarker (figs. 17-5 and 17-6). The bulk density of bark from all debarkers was diminished by hogging and screening; the lowest value observed was 9.3 lb/cu ft for hogged and screened airdry oak bark. Vibration of hogged bark increased its bulk density, but only with airdry soft hardwood barks was bulk density increased to more than before hogging.

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[6] Vidrine, C., and G. E. Woodson. Bulk densities of selected pine-site hardwood materials. Final Report FS-SO-3201-3.27, dated November 25, 1980, U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Pineville, La.

TABLE 13-42—*Bulk densities of green and airdry bark residue from pine-site hardwoods of two density classes, removed by four types of mechanical debarkers, as loaded and after hogging, screening, and vibrating* (Vidrine and Woodson; see text footnote 6)[1,2]

Bark condition and debarker type	Red maple, sweetgum, and yellow-poplar		Hickory and oak	
	Green	Airdry	Green	Airdry
	Lb/cu ft *(Percent moisture content)*			
As loaded into an open-top railcar from:				
Drum debarker	24.3 (87)	13.4 (12)	20.4 (48)	16.2 (12)
Drum debarker	—	—	23.3[3] (68)	13.7[3] (14)
Ring debarker	20.5 (62)	14.3 (13)	30.2 (56)	18.6 (21)
Rosser-head debarker	20.3 (50)	15.3 (13)	19.3 (55)	18.2 (15)
Post peeler (floating cutterhead)	24.0 (80)	15.1 (13)	24.8 (49)	19.2 (17)
Hogged through ½-inch screen	16.2 (78)	13.3 (13)	14.2 (49)	9.3 (15)
Hogged through ½-inch screen and vibrated	17.9 (78)	17.1 (13)	16.7 (49)	11.1 (15)

[1] Bark was collected at mills in north Louisiana.

[2] The first value is bulk density, lb/cu ft; the second value (in parentheses) is moisture content, percent of ovendry weight.

[3] Mixed hardwood bark; about 50 percent oak, 25 percent sweetgum, and 25 percent other hardwoods.

Chow et al. (1973) measured the bulk density of bark residue of two oak species sampled at Illinois mills, then dried to about 6-percent moisture content, hammermilled and disk-refined—with results as follows:

Species and treatment	Bulk density
	Lb/cu ft
Red oak sp.	
Unrefined	15.5
Hammermilled through ½-inch screen	20.5
Disk-refined	10.5
White oak	
Unrefined	7.0
Hammermilled through ½-inch screen	18.0
Disk-refined	6.9

These data suggest that if oak bark is very dry, e.g., 6-percent moisture content, its bulk density can be increased by hammermilling but not by disk refining.

Wartluft (1972, 1974a) found that bulk density of bark residue from mixed hardwood sawlogs from West Virginia differed according to debarker type: bark residue from a rosser-head had greater bulk density (330 lb/cu yard) than that from floating cutterheads (277 lb/cu yard), based on volume when green and weight when ovendry. Pooling data from mills having debarkers of both types, bulk densities varied with species, as follows:

Species	Ovendry weight and green volume	Green weight and green volume
	--------------*Lb/cu yard*	--------------
Hickory sp.	177	287
Maple sp.	403	625
Oak, chestnut	277	457
Oak, red sp.	312	509
Oak, white sp.	329	439
Yellow-poplar	214	419

These bulk densities based on green weight and volume averaged 456 lb/cu yard or 17 lb/cu ft—not greatly different than the value in table 13-42 for green hickory and oak debarked by rosserhead (19 lb/cu ft).

Choong and Cassens (1976b) measured the bulk density of hardwood bark and sawdust of a mixture of species from mills near Baton Rouge, La.; bulk densities averaged as follows (moisture content averaged 107 percent of dry weight in the fresh residue and 184 percent in the piles):

Basis	Fresh	Piled
	----*lb/cu*	*ft*---
Green volume and green weight	24.0	29.4
Green volume and ovendry weight	11.8	10.8

STRENGTH

Martin and Crist (1968) used modifications of standard test procedures and smaller than standard specimens to evaluate the mechanical properties of bark from eight hardwoods commonly found on southern pine sites; specimens were collected in Georgia, Virginia, and Michigan but were not organized for statistical analysis of within-species variations. Specimens were tested dry at the equilibrium moisture content they attained during a month or more of storage in the laboratory.

Crushing strength.—In the hardwood barks evaluated, no significant relationships between density and compressive properties were found. Crushing strength ranged from 66 to 320 kg/cm^2 longitudinally, 26 to 216 kg/cm^2 radially, and 51 to 158 kg/cm^2 tangentially.

Hardness.—Because of small sample size, Martin and Crist (1968) used an 0.222-inch ball (instead of the standard 0.444 inch) to measure hardness. They found that the force to impress the ball to half its depth (H, kg) was positively correlated with specific gravity (G) based on ovendry volume and weight; the following equation accounted for 60 percent of the observed variation:

$$H = -26.6 + 144.5G \qquad (13\text{-}7)$$

For comparability with standard tests, the data were converted to results expected with an 0.444-inch ball (fig. 13-74).

Shear strength.—Martin and Crist (1968) found that shear failures in the tangential plane tend to occur along periderms, and that radial shear strength of hardwood barks is higher than tangential strength. Radial values (about 575 psi) did not vary significantly with bark specific gravity, whereas tangential values did, although specific gravity (G, based on ovendry weight and volume) accounted for only 17 percent of the variation in shear strength as follows (fig. 13-75):

$$\text{Shear strength in tangential plane, kg/cm}^2 = 9.17 + 29.52\,G \qquad (13\text{-}8)$$

Modulus of rupture.—In bending, bark is weakened by shear failures along the periderms; beams of bark therefore tend to separate into layers when stressed. Modulus of rupture is positively correlated with specific gravity (G) based on ovendry weight and volume as follows:

$$\text{Modulus of rupture, kg/cm}^2 = 59.6 + 143.5\,G \qquad (13\text{-}9)$$

The relationship (fig. 13-76) accounted for 16-percent of the variation observed by Martin and Crist (1968).

Tensile strength.—The fiber in hardwood barks gives them more tensile strength parallel to the grain than bark of the southern pines, which lacks fibers. Martin and Crist (1968) found that specific gravity (G) based on ovendry volume and weight accounted for 14 percent of the variation observed in tensile strength of dry hardwood barks, as follows (fig. 13-77):

$$\text{Tensile strength, kg/cm}^2 = 30.6 + 68.6\,G \qquad (13\text{-}10)$$

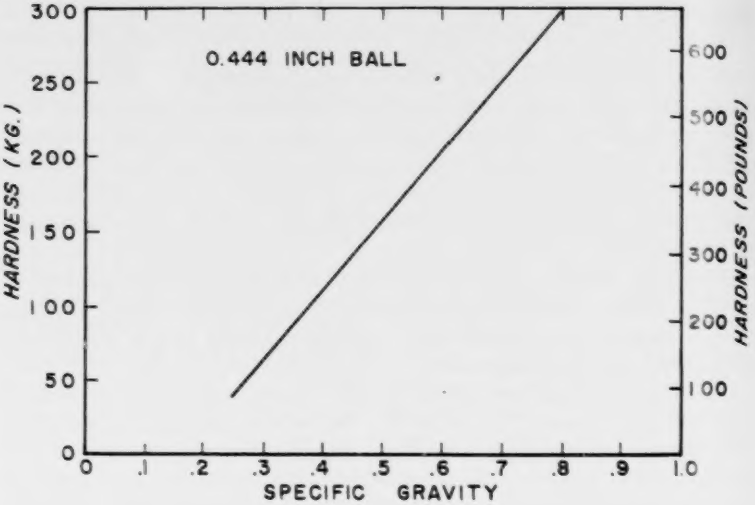

Figure 13-74.—Hardness of dry bark related to specific gravity. Data from 12 hardwood species and seven pine species (including five southern pines) were pooled to compute this relationship (Drawing after Martin and Crist 1968.)

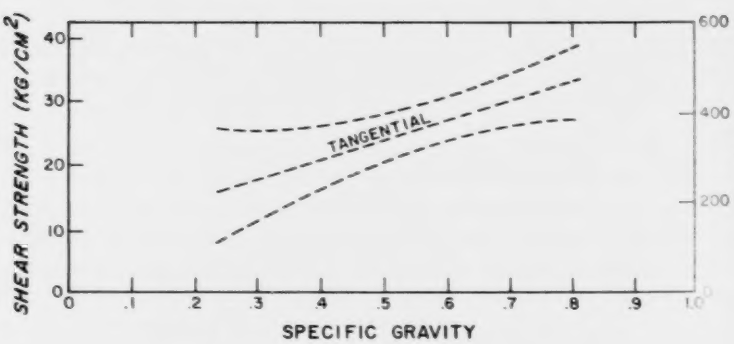

Figure 13-75.—Shear strength of hardwood barks when the plane of failure is in the tangential plane, related to bark specific gravity (G) based on ovendry volume and weight; 95-percent confidence limits are indicated. (Drawing after Martin and Crist 1968.)

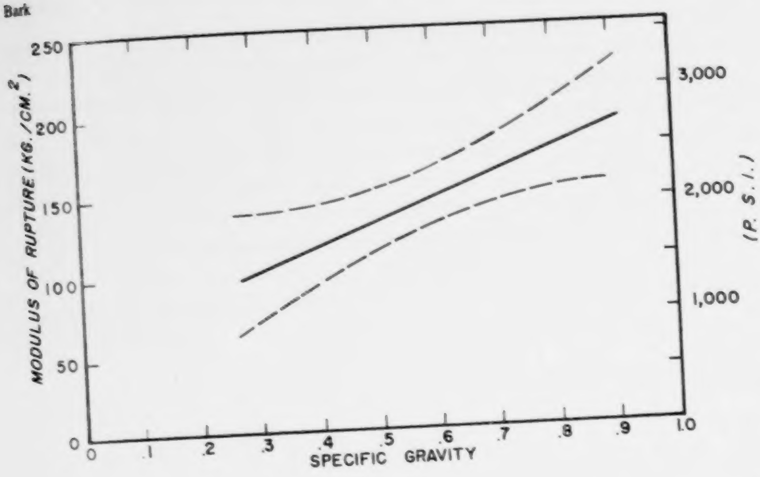

Figure 13-76.—Modulus of rupture of dry bark in static bending as related to specific gravity (basis of ovendry volume and weight). Dashed lines indicate 95-percent confidence limits. Data from 12 hardwood species and seven pine species (including five southern pines) were pooled to compute this relationship. (Drawing after Martin and Crist 1968.)

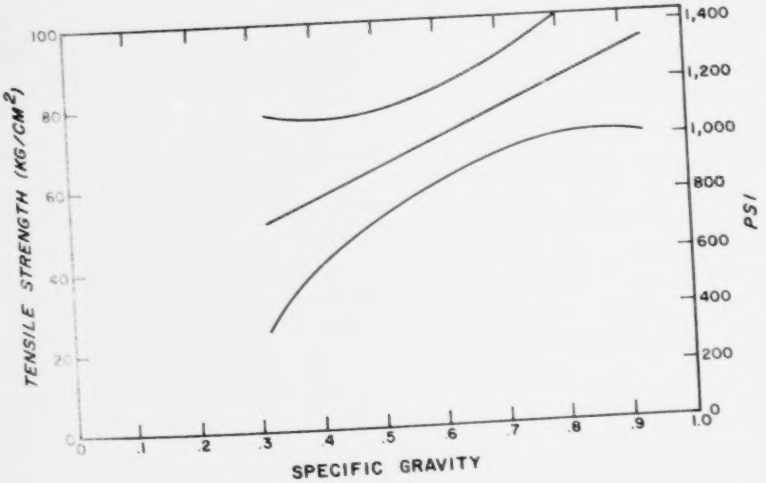

Figure 13-77.—Tension strength at failure of dry hardwood barks tested parallel to the grain, related to specific gravity (basis of ovendry volume and weight). Dashed lines indicate 95-percent confidence limits. Data from 12 hardwood species were pooled to obtain these graphs. (Drawing after Martin and Crist 1968.)

Toughness.—Martin and Crist (1968) found that hardwood barks were tougher than the southern pine barks tested. Toughness of dry bark from five southern hardwoods was as follows; yellow-poplar bark was significantly tougher than all others tested:

Species	Replications	Toughness
		kg-cm/cm³
Elm, American	4	0.730
Oak, black	9	.735
Oak, white	8	.751
Oak, chestnut	6	1.021
Yellow-poplar	5	1.586

SHRINKAGE AND EXPANSION

Martin (1968) has given limited information on volumetric expansion, and Martin and Crist (1968) have published data on dimensional expansion of bark when moistened from ovendry condition to fiber saturation, as follows:

Statistic	American elm	Chestnut oak	Northern red oak
Volumetric expansion, percent of wet volume			
Inner bark	14.6–14.8	—	14.6
Outer bark	12.5–13.6	—	18.5
Longitudinal expansion, percent of ovendry dimension	0.4- 1.4	3.6-4.6	—
Radial expansion, percent of ovendry dimension	7.2- 9.2	4.7-6.2	—
Tangential expansion, percent of ovendry dimension	7.9- 9.2	5.0-9.7	—

Longitudinal shrinkage of bark, while generally less than transverse shrinkage, is substantially greater than that observed in normal wood of the same species.

In the absence of more complete information, Martin (1968) assumes that bark does not change volume at moisture contents above fiber saturation point, and that shrinkage between fiber saturation point and the ovendry condition is linear. On this basis, he advanced the following formulas for computing the volume (V_M) of a piece of bark at any moisture content, given the wet volume (V_W), or the ovendry volume (V_O):

$$V_M = (0.8647 + 0.00534M)\ V_W \qquad (13\text{-}11)$$

$$V_M = (1 + 0.00618M)\ V_O \qquad (13\text{-}12)$$

where M is the moisture content as a percentage of ovendry weight. He proposes 25.3 percent as the fiber saturation point for bark. These formulas are not specific to pine-site hardwoods, but are based on pooled data for numerous species.

ELECTRICAL CONDUCTIVITY AND RESISTIVITY

Conductivity and its reciprocal, resistivity, are defined in text related to figure 9-12 in the introductory paragraphs of section 9-2.

Okoh (1976) provided data on longitudinal resistivity of wood and radial resistivity of bark of 21 hardwoods from pine sites (table 3-1) when subjected to a direct current gradient of 50 volts; wood specimens measured 3 mm along the grain, and matching bark specimens of the same species were about 1.5 mm in the radial direction. He found that the logarithms of resistivities (log r) of wood (and bark) specimens were related to the logarithms of their moisture contents (log M) as follows:

$$\log r = A - (B \log M) \qquad (13\text{-}13)$$

With data from all species pooled, resistivity of stembark is not significantly different from that of stemwood (fig. 9-12), although differences may be significant in some species. Data on wood resistivity of all 21 species are shown in table 9-3. Data from bark of these species (table 13-43) indicate that cherrybark oak has lowest resistivity (most conductivity) and sweetgum has highest resistivity (least conductivity), as follows:

Statistical and moisture content	Average	Minimum (cherrybark oak)	Maximum (sweetgum)
Log r			
12 percent moisture content	8.261	7.456	9.233
18 percent moisture content	6.348	5.646	7.532
Resistivity			
12 percent MC (ohm cm)	182.39×10^6	28.58×10^6	$1,710.02 \times 10^6$
18 percent MC (ohm cm)	2.23×10^6	$.44 \times 10^6$	34.04×10^6

TABLE 13-43—*Logarithm of resistivity (at 25°C) radially perpendicular to grain of stembark from 6-inch trees of 22 hardwood species grown on southern pine sites, at 12- and 18-percent moisture contents, and regression coefficients for the equation: log resistivity, ohm-cm = A − (B log moisture content, percent)* (Okoh 1976, p. 148)

Species	Regression coefficients		Correlation coefficient	Logarithm of resistivity at	
	A	B	R	12%MC	18%MC
Ash, green	21.163	11.739	0.992	8.495	6.428
Ash, white	20.627	11.017	.993	8.737	6.797
Elm, American	21.533	12.198	.996	8.369	6.221
Elm, winged	19.398	10.818	.995	7.723	5.818
Hackberry	20.769	11.117	.999	8.772	6.814
Hickory	20.792	11.227	.997	8.676	6.699
Maple, red	21.961	11.944	.998	9.071	6.968
Oak, black	18.713	10.304	.999	7.593	5.779
Oak, blackjack	18.891	10.057	.999	8.038	6.267
Oak, cherrybark	18.552	10.282	.999	7.456	5.646
Oak, chestnut	—	—	—	—	—
Oak, laurel	19.265	10.426	.999	8.013	6.177
Oak, northern red	19.737	10.997	.999	7.869	5.932
Oak, post	17.757	8.839	.999	8.219	6.662
Oak, scarlet	19.819	10.737	.999	8.232	6.341
Oak, Shumard	19.245	10.639	.999	7.764	5.891
Oak, southern red	20.117	11.160	.999	8.073	6.108
Oak, water	19.209	10.546	.999	7.828	5.971
Oak, white	19.568	10.834	.999	7.877	5.969
Sweetbay	21.710	11.997	.998	8.763	6.650
Sweetgum	19.660	9.662	.998	9.233	7.532
Tupelo, black	20.149	10.986	.992	8.293	6.359
Yellow-poplar	20.914	11.376	.997	8.638	6.634
Average	19.980	10.859	.998	8.261	6.348
Standard deviation	1.101	.781		.487	.462
Coefficient of variation	5.511	7.192		5.901	7.276

SOUND ABSORPTION

Bark of hardwood trees is not used as a structural material so neither sound velocity measurements for non-destructive evaluation of mechnical properties, nor sound transmission losses across partitions or floors of bark have been reported.

It would be possible, however, to make acoustical tile from natural hardwood bark for the absorption of sound. The effectiveness of a room surface in absorbing sound is expressed in terms of the absorption coefficient, α, which is the fraction of the incident sound energy absorbed or otherwise not reflected from the surface. If measured in an impedance tube (see Reethof et al. 1976 for explanation of technique), the absorption coefficient is computed from the following relationship:

$$\alpha = 1 - \left(\frac{S - 1}{S + 1}\right)^2 \qquad (13\text{-}14)$$

where α is the absorption coefficient, the ratio of the absorbed to incident acoustic energy, and S is the ratio of the maximum to minimum acoustic pressures in the impedance tube.

The absorption coefficient of a typical acoustical tile cemented to a wall ranges from about 0.15 at low frequencies (125 cycles per second, Hz) through 0.70 to 0.95 at mid frequencies (500 to 1,000 Hz), to about 0.65 at high frequencies (4,000 Hz). Panels of wood, hardboard, or plywood adhered to rigid surfaces are poor sound absorbers; they absorb only 5 to 10 percent and reflect more than 90 percent. Leaving the wood surface rough improves absorption only slightly. On the other hand, well designed, porous acoustical tiles made of wood fiber may absorb up to 90 percent and reflect only 10 percent of impinging sound in a broad spectrum of the higher audible frequencies.

One might speculate that fissured bark surfaces of hardwoods would absorb sound better than wood, hardboard, or plywood. Reethof et al. (1976) found from tests of bark from several softwood and hardwood species that moisture content of bark does not significantly alter its absorption, but different bark samples of each species differed appreciably in sound absorption coefficient. Of the species tested, only mockernut hickory (fig. 13-78) had average absorption coefficient above 0.10; it had coefficients from 0.02 to 0.23 at frequencies above 1,250 Hz. The wide variation in this species correlated well with differences in bark thickness; a thin-barked sample consistently gave low values. The high absorption of mockernut hickory bark may be due to its shale-like layers with spaces between them. The spaces may allow individual layers to vibrate, transforming the incident acoustical energy into mechanical energy. Figure 13-78 illustrates the differences observed between hickory and northern red oak, and also among-sample variation.

In spite of these rather low values for native barks, it is possible that acoustical tiles suitably reconstituted from bark fibers and particles could be competitive in sound absorbency with wood-fiber tiles. The dark color of bark and its high content of extractives are deterrents, however.

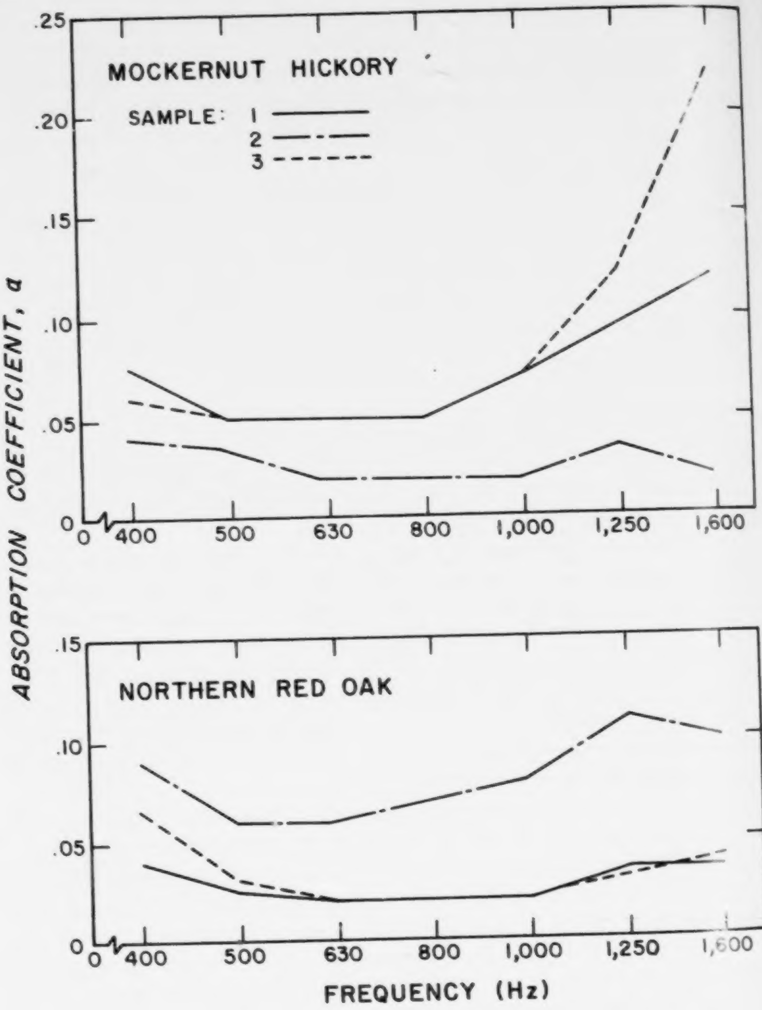

Figure 13-78.—Absorption of normal-incidence sound of various frequencies by dry bark of mockernut hickory (top) and northern red oak (bottom). Drawing after Reethof et al. 1976.)

SPECIFIC HEAT

Specific heat is defined in the initial paragraphs of section 9-2 related to equations 9-8 through 9-11. Published data on the specific heat of softwood barks—particularly those of the southern pines—were reviewed by Koch (1972, p. 509-512). Few data are available on the specific heat of hardwood barks.

Martin (1963) determined from a study of 20 bark specimens from 8 tree species (most of which were hardwoods) that the specific heat of ovendry bark at 56°C was 0.329.

Specific heat of wet bark.—For bark at 22°C and in the range from 0 to 27 percent moisture content, Koljo (1950) observed a simple additive relation (estimated from his graph):

$$C_{pu}(1 + u) = u + 0.320$$

where:

c_{pu} = specific heat of moist bark (13-15)

u = moisture content expressed as a fraction of dry weight

then:

$$c_{pu} = \frac{u + 0.320}{1 + u}$$

In other words, at 22°C the specific heat of ovendry bark was 0.320 and the specific heat of moist bark was 0.382 at 10 percent moisture and 0.433 at 20 percent moisture.

In 19 tests on six species (of which some were hardwoods), Martin (1963) measured the excess specific heat of bark at fiber saturation point. For saturated bark ($u = 0.27$), he obtained an excess specific heat of 0.083 calorie per gram dry bark per degree C. (observed in bark at 56°C).

With some simplifying assumptions, Martin concludes that the specific heat of moist bark (expressed in terms of the bark-water mixture) is:

$$c_{pu} = \frac{u + c_p}{u + 1} + \frac{\Delta c}{u + 1} \qquad (13\text{-}16)$$

where:

c_{pu} = specific heat of bark-water mixture

c_p = specific heat of ovendry bark at the temperature in question

u = moisture content expressed as a fraction of the weight of dry bark

Δc = excess specific heat at the temperature in question. In calories per gram dry bark per degree C., $\Delta c = \left(\frac{u}{0.27}\right)(0.083)$; at moisture contents of 27 percent and higher, $\Delta c = 0.083$.

If it is assumed that:

$u = 0.25$

$c_p = 0.329$ for ovendry bark at 56°C.

$\Delta c = (0.083)\left(\frac{0.25}{0.27}\right)$ calorie per gram of ovendry bark per degree C. at 25-percent moisture content.

Then, from Martin's formula, the specific heat of moist bark equals:

$$c_p = \frac{0.25 + 0.329}{0.25 + 1} + \frac{(0.083)\left(\frac{0.25}{0.27}\right)}{0.25 + 1},$$

$$= 0.4632 + 0.0615$$
$$= 0.525$$

At 56°C then, 0.525 calorie is required to raise 1 g of moist bark (25 percent moisture content) 1° C. This is 13.4 percent greater than the relative portions of bark and water would suggest (0.463). Martin's conclusions on the excess specific heat caused by addition of water to bark were based on data from several species; it is likely, however, that the concept is applicable to the hardwood barks under study.

HEAT TRANSMISSIVITY

Thermal conductivity and diffusivity, together with the units in which they are measured, are defined in section 9-3.

Thermal conductivity.—In tests of 10 species including several southern hardwoods, Martin (1963) found that dessicated bark has a thermal conductivity about 20 percent less than wood of the same density. In southern hardwoods evaluated, bark conductivity was greatest in the longitudinal direction and least in the radial direction, as follows (Martin 1970):

Species	Ratio of tangential/radial conductivity	Ratio of longitudinal/tangential conductivity
Elm, American	1.085	1.145
Oak, black	—	1.124
Oak, northern red	—	1.115
Oak, white	1.054	—

The ratio greater than unity for tangential/radial conductivity contrasts with that for wood, where radial conductivity is the greater of the two. In wood, the rays are intact and possibly serve as radial conductors, whereas those in bark are discontinuous because of obliteration.

Transverse (combination of radial and tangential) thermal conductivity values for 10 barks—including a number of southern hardwoods—have been expressed by Martin (1963) in terms of a regression equation requiring the measurement of specific gravity and moisture content, as follows:

$$k = \left[5.026S + (13.241)(S)\left(\frac{\text{percent moisture content}}{100}\right) - 0.202 \right] 10^{-4} \tag{13-17}$$

where:

k = thermal conductivity, cal. per cm., sec., °C.

S = specific gravity based on ovendry weight and volume at test.

To convert k to B.t.u. inch per sq. ft., hr., °F., divide by 0.0003445.

Martin (1970) has also provided a method of computing the conductivity for each of the three directions, given *k* as stated above; because the directional differences in barks are so small, the formulae are not reproduced here.

Using equation 13-17, Martin (1963) computed the thermal conductivity of shortleaf and loblolly pine barks to be about (1.80) (10^{-4}) cal/cm, sec, °C. This is equivalent to 0.52 Btu inch per sq ft, hr, °F, and is somewhat less than the value for wood (fig. 9-16). The hardwood barks vary significantly in thermal conductivity because of their wide range of specific gravity and moisture content.

The low conductivity of bark is probably attributable to the expanded parenchyma in phloem plus multiple zones of both expanded phelloderm and thin-walled cork cells.

The thermal conductivity of solid southern pine bark is about 50 percent higher than that of commonly used insulating materials but some of the hardwood barks are excellent insulators (Martin 1963).

Thermal diffusivity.—Martin (1963) computed values for thermal diffusivity of barks in the specific gravity range from 0.20 to 0.80, at moisture contents from 0 to 100 percent of ovendry weight, and at temperatures from 0 to 100°C. His values ranged from (10.6)(10^{-4}) to (18.3) (10^{-4}) cm²/sec.

As an average value of thermal diffusivity for bark, he concluded that (13) (10^{-4}) cm²/sec was best. This is equivalent to 0.00020 in²/sec and is slightly lower than typical for wood (.00025 in²/sec).

HEAT OF COMBUSTION

Heat of combustion, the total quantity of heat evolved by the complete combustion of a unit mass of substance—usually stated as Btu/ovendry pound or cal/g—is measured by oxygen-bomb calorimetry as described in text related to table 9-12. Heats of combustion of stembark, branchbark, stemwood, and branchwood from small pine-site hardwoods all range from 6,840 to 8,123 Btu/ovendry pound (table 9-12). The averages are as follows:

Tree portion	Heat of combustion (higher heating value)
	Btu/ovendry pound
Stembark	7,593
Branchbark	7,623
Branchwood	7,784
Stemwood	7,827

Sandala et al. (1981) found that outer bark of white and northern red oaks has about 30 percent higher heat of combustion than inner bark of these species, largely because outer bark has about twice the Klason lignin content of inner bark. Hough (1969) found that outer bark of sweetgum had 24 percent more heat of combustion (4,709 cal/ovendry g or 8,476 Btu/lb) than inner bark (3,810 cal/g, or 6,858 Btu/lb).

Harder and Einsphar (1978) found that the heat of combustion of hardwood barks diminished as ash content increased (correlation coefficient = −0.836) but increased as extractives content increased (correlation coefficient = +0.518). Data of Sandala et al. (1981) indicate that heat of combustion of hardwood barks is positively correlated with lignin content; in white and northern red oaks, Klason lignin had from 1.5 to 2.3 times the heat of combustion of holocellulose (table 13-44).

Pine-site trees 6 inches in dbh.—As noted earlier, heats of combustion (ovendry basis) of stembark and branchbark are given in table 9-12. For conversion to available heat see table 13-30 for the moisture contents of these components.

Bark of pulpwood species, ovendry basis.—Harder and Einspahr (1976, 1978) reported Btu/ovendry lb and Btu/cu ft of 12 hardwood species commonly found on southern pine sites. Of the twelve, yellow-poplar had the highest heat content per pound but hickory had highest heat content per cubic foot (table 13-45).

Choong's (1974) value for stembark of sweetgum sampled from two upland and two bottomland trees 20 inches in dbh growing near Baton Rouge, La. (7,727 Btu/ovendry lb) agrees closely with the value of Harder and Einspahr.

Millikin (1955) gives the heat of combustion of stembark from soft elm as 7,600 Btu/ovendry lb and that of bark from soft maple as 8,100 Btu/ovendry lb. These values were based on five logs of each species group sampled from each of several mills in eastern Canada.

TABLE 13-44—*Average and range of heats of combustion (higher heating value) of ovendry stembark components of northern red oak and white oak sampled in Pennsylvania* (Sandala et al. 1981)

Species and component[1,2,3]	Inner bark		Outer bark	
	Average	Range	Average	Range
	Cal/g[4]			
Oak, northern red				
Unaltered bark	4,596	4,384–4,709	6,019	5,967–6,089
Extracted bark	3,992	3,476–4,331	6,035	6,009–6,065
Holocellulose	3,156	2,836–3,391	4,604	4,109–5,160
Lignin	7,208	6,779–7,871	7,023	6,788–7,271
Oak, white				
Unaltered bark	3,748	3,281–4,072	4,852	4,185–5,202
Extracted bark	3,798	3,670–4,009	5,096	4,938–5,205
Holocellulose	2,590	2,382–2,957	3,411	3,146–3,918
Lignin	5,836	5,512–6,044	6,983	6,778–7,167

[1] Extracted bark prepared with solvents, used in succession as follows: diethyl ether, alcohol-benzene, cold water, and hot water.

[2] Holocellulose was prepared by the acid chlorite method.

[3] Klason lignin procedures followed TAPPI standard T 13 os-54.

[4] To convert to Btu/lb multiply these values by 1.80.

TABLE 13-45—*Heat of combustion of ovendry stembark of 12 hardwood species commonly found where southern pines grow* (Harder and Einspahr 1976, 1978)

Species	Heat of combustion (higher heating value), Btu per Ovendry pound	Heat of combustion (higher heating value), Btu per Cubic foot[1]
	Btu	*Btu*
Ash, green	8,367	235,113
Ash, white	8,453	263,734
Hickory, shagbark	8,423	378,193
Maple, red	8,293	310,158
Oak, black	8,340	353,616
Oak, northern red	8,896	361,178
Oak, post	6,773	236,378
Oak, southern red	8,371	365,813
Oak, white (southern sample)	8,046	280,805
Sweetgum	7,650	200,430
Tupelo, black	8,102	222,805
Yellow-poplar	8,956	212,257

[1] Volume in place on stem.

Air-dried bark of five pulpwood species.—Chang and Mitchell (1955) determined the heat of combustion of airdried stembark of 24 North American pulpwood species, five of which commonly occur on southern pine sites, as follows:

Species	Moisture Content at test	Heat of combustion (higher heating value)
	Percent	*Btu/pound*
Elm, American	6.7	6,921
Oak, red sp.	4.4	8,030
Oak, white	6.5	6,995
Tupelo, black	6.0	7,936
Sweetgum	6.2	7,450

Root bark.—Heat of combustion (higher heating value) of rootbark from 6-inch pine-site trees was found maximum in southern red oak (8,273 Btu/ovendry pound), minimum in hackberry (6,997 Btu/pound), and averaged 7,657 Btu/ovendry pound. See table 14-12.

Barks of various moisture contents.—The heat content of green or wet bark of known moisture content is that of the dry weight of bark contained in the wet bark. If a bark sample is half water, by weight, then its heat content per pound when wet is half the heat of combustion of the ovendry bark. Murphey and Cutter (1974) experimentally measured the relationships between the heat of combustion (higher heating value) of yellow-poplar bark and its moisture content (fig. 13-79).

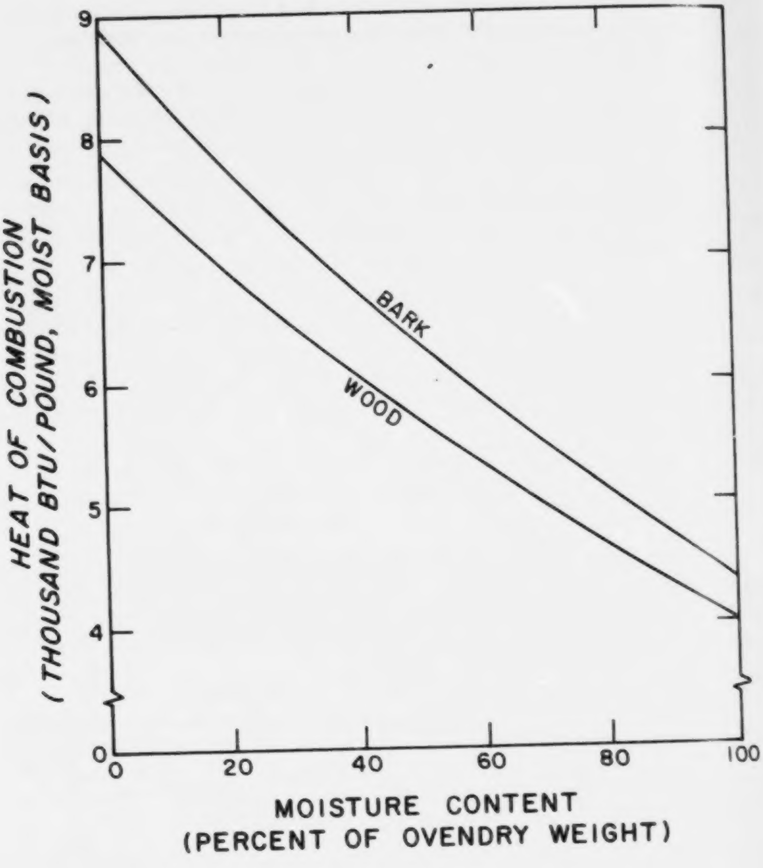

Figure 13-79.—Experimentally determined heat of combustion (higher heating value) determined with an oxygen-bomb calorimeter, related to the moisture content of yellow-poplar bark and a composite sample of wood from five species of northeastern hardwoods. (Drawing after Murphey and Cutter 1974.)

Bark residues.—Southern sawmills cutting hardwoods typically use ring, rosser-head, or floating-cutterhead debarkers. (See chapter 17 for illustrations of typical equipment.) All of these machines remove some wood together with the bark. Bark residues at sawmills are therefore composed of a mixture of bark and wood with heat content dependent on the ratio of the bark-wood mixture, the species-mix at the mill, and the moisture content of the residue.

Choong and Cassens (1976b) sampled hardwood bark and wood residues from six sawmills near Baton Rouge, La., that cut a mixture of southern hardwoods. One sample of fresh residue was obtained at each mill and at least two samples from each mill's residue pile. Moisture contents of the samples were determined and heats of combustion determined by oxygen-bomb calorimeter; this higher heating value is shown in table 13-46, together with residue moisture content. Baton Rouge rainfall averaging 62.3 inches/year accounts for the high moisture content of the piled residue.

TABLE 13-46—*Heat of combustion (higher heating value) per ovendry pound of fresh and piled sawmill residues of hardwood bark and wood, and residue moisture content* (Choong and Cassens 1976b)

Residue and statistic	Heat of combustion (higher heating value)	Moisture content
	Btu/ovendry pound	*Percent of ovendry weight*
Fresh residue		
Average	8,017	107
Range	7,891–8,228	69–165
Piled residue		
Average	8,046	184
Range	7,815–8,862	88–380

Moisture content and available heat.—As noted previously, heats of combustion are determined with an oxygen bomb calorimeter. Values obtained are somewhat higher than those recovered in practice because the calorimeter is closed and the products of combustion are contained. Thus, on cooling, water vapor is condensed and releases its heat of vaporization. In an industrial furnace, this heat is normally lost to the atmosphere. The heat of combustion measured by a bomb calorimeter is called the **higher heating value.** The **lower heating value** is obtained by subtracting the heat of vaporization of the water formed in combustion.

The economic value of a fuel will depend both on its heating value and moisture content. High moisture content is detrimental in two ways. First, it reduces the available heat of the fuel. The higher heating value of a fuel does not change with increasing moisture content, but the available heat does change (equation 13-18) because there is simply less fuel per unit weight.

Available heat = (percent wood) x (higher heating value) (13-18)

Thus, for stembark of 6-inch pine-site hardwoods:

Moisture content	Available heat (higher heating value)
Percent of ovendry weight	*Btu/lb*
0 (ovendry)	7,593
50	5,695
100	3,796

High moisture content also reduces furnace efficiency, because heat energy is lost up the stack in vaporizing the moisture in the fuel. Vaporization of fuel moisture is the first stage in combustion; thus heat energy must raise the moisture temperature from ambient (70°F) to the boiling point (212°F). Additional heat energy is required to vaporize the water to steam at 212°F. Heat energy is also lost in raising the steam temperature to that of the furnace stack gases. Steam tables can be readily used to calculate the amount of energy required to heat and evaporate water. For example, if the stack temperature is 500°F, the calculated heat energy lost in changing the water at 70°F to steam at 500°F and 14.7 psi is 1,250 Btu/lb of water (Wiley 1976).

In an effort to provide operators of boilers fired with bark residues with a convenient measure of net heat values of fresh residue at 107 percent moisture content, Choong and Cassens (1976b) adjusted higher heating values observed in bark residues according to the procedure described by Koch (1972, p. 1382 and 1383); this procedure assumes that each pound of water present in the residue will remove 1,210 Btu up the flue, that 0.55 pound of water will be formed in burning the hydrogen in 1 pound of fuel so that 660 Btu are lost from this source, and that another 690 Btu are lost up the stack in other hot flue gases for each pound of dry fuel present. The net Btu value of 1 lb of ovendry fuel residue collected fresh is therefore 6,667 Btu; moist residue fuels have the net heat values shown in figure 13-80. For example, the net Btu value of 1 lb of fresh residue at 107 percent moisture content is:

(8,017 Btu x 0.483 lb dry wood) − (1,210 Btu x 0.517 lb water in the wood)
− (660 Btu x 0.483 lb dry wood) − (690 Btu x 0.483 lb dry wood)
= 2,594.5 Btu

White et al. (1983)* found that particulate fuels stored outside in Virginia undergo complex changes in heat of combustion and moisture content. They concluded that higher heating values of hardwood whole-tree chips and hardwood bark declined by about 9 and 7 percent and sawdust by about 3 percent during one year's storage in 15-foot cone-shaped piles; the observed decrease occurred only after about 4 months of storage. Increases in the moisture content of such particulate fuels, and subsequent decrease in higher heating value, resulted in a significant decrease in the average net heating value of stored fuels.

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*White, M.S., M.L. Curtis, R.L. Sarles, and D.W. Green. 1983. Effects of outside storage on the energy potential of hardwood particulate fuels: Part II. Higher and net heating values. Forest Products Journal. 33 (11/12):61-65.

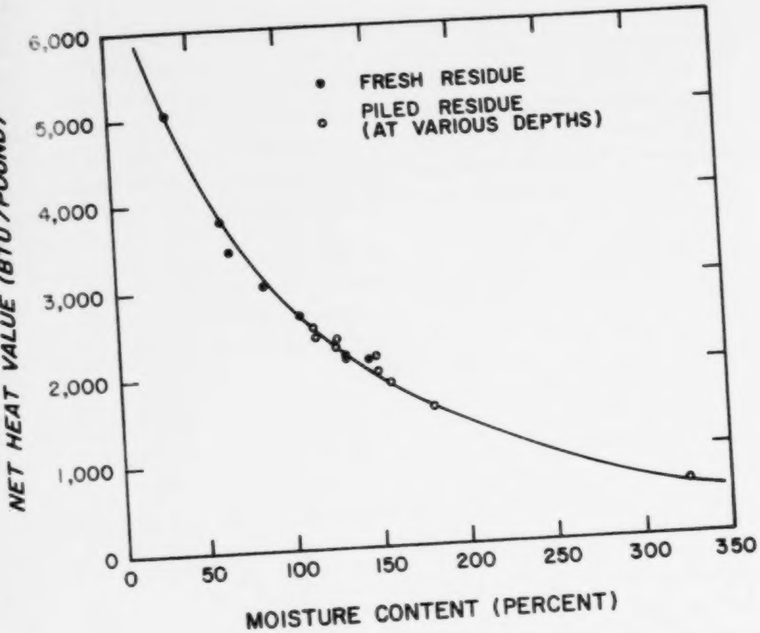

Figure 13-80.—**Net heat values in Btu/pound of hardwood bark-wood residue (moist-weight-basis) at various moisture contents. (Drawing after Choong and Cassens 1976b.)**

Most of the loss in average net heating value occurred during the first 2 to 4 months of storage, due principally to increases in fuel moisture content at the pile surface.

13-7 USES IN AGRICULTURE AND LANDSCAPING

Hardwood bark, as well as whole-tree chips, wood chips, sawdust, and planer shavings, can be useful as ground cover, mulch, and soil amendment for growing plants, and as bedding for animals, especially poultry. As ground cover or mulch, bark suppresses weeds, conserves moisture, insulates the soil, and improves appearances. When decayed, it provides humus which replenishes soil organic matter, improving tilth and moisture-holding capacity, and slowly releasing nutrients for plant use. For animal bedding, its advantages are absorbency and resistance to compaction.

In productive soils, organic colloids act as cement to bind fine mineral particles together into larger aggregates, improving soil porosity. Soil microorganisms break down raw organic materials and—as they die and decompose—release nutrients, including fixed nitrogen, in forms available to plants. Because these and other soil processes continually deplete soil organic materials, organic amendments are applied where crop or other residues are inadequate.

The composition of organic materials greatly affects their usefulness to plants. Although not the primary source of minerals, the amount and character of minerals they contain can be important. Potassium and phosphorous are major plant nutrients, and are generally desirable; excess of salts may be detrimental. Lignin is a major constituent of humus. Carbohydrates provide food for micro-organisms; since their metabolism requires nitrogen, excessive amounts of carbohydrate may deplete nitrogen available to plants unless accompanied by a nitrogenous fertilizer.

Since soil acidity affects plants and the efficiency of fertilizers, the pH of organic additives is often important. Most crop and ornamental plants, as well as trees, prefer neutral or slightly acid soils; a few require acid or highly acid soil. Only for such special applications are highly acid additives preferred over materials whose pH approaches neutral.

BARK AND WOOD pH

Bark of small pine-site hardwoods is somewhat acidic, averaging about 5.2 in pH with range among species from about 4.8 to 5.7; stemwood of these trees also has average pH of about 5.2 with range among species from 4.4 to 5.7 (table 6-23). McCool (1949) and Salomon (1953) found that soil pH, measured 2 years after the action, was little affected by incorporation of 30 tons of chips per acre. Lunt and Clark (1959) suggest that if control of soil pH shift from incorporation of bark or wood is required, the use of 10 lb of limestone per cubic yard of bark and wood fragments would suffice, but not all authorities agree on this prescription.

Peat moss, another organic material frequently used in horticulture as a soil amendment, commonly has a pH of about 3.5 (Lunt and Clark 1959).

NITROGEN DEPLETION

Finely divided bark or wood from southern hardwoods added to soil decomposes rapidly, but bark decomposes less rapidly than wood in soil. Since the micro-organisms that cause decomposition require nitrogen, the decomposition process temporarily robs plants of this necessary nutrient. The problem can be met in several ways—by prior use of the wood or bark as mulch or as animal bedding, by addition of nitrogen through ammoniation or addition of fertilizer, or by prior composting. Another approach is treatment of the wood or bark to render it resistant to decay before its application as a soil amendment.

PEAT MOSS IN RELATION TO HARDWOOD BARK, SAWDUST, AND WOOD CHIPS

Hardwood bark and wood fragments must compete against peat moss in price and function if they are to successfully penetrate the market for soil amendments. Bulk densities of the competitive products vary, but generally peat moss has lower bulk density than the hardwood products, except for planer shavings and flakes (tables 16-44 and 13-42):

Product	Bulk density Green	Bulk density Airdry
	Lb/cu ft	
Bark hogged through a ½-inch screen	14–18	9–17
Whole-tree chips	23–31	—
Wood pulpchips	21–29	—
Sawdust	19	11
Planer shavings	7–17	5–7
Wood flakes	5–15	2–6
Peat moss	—	8

Bulk density is important since it affects weight of potted products and this, in turn, affects handling and transportation costs. None of the products changes much in bulk density on exposure. Bark, sawdust, and peat moss all produce about the same percent drainable pore space where mixed with an equal volume of sand—a factor important to soil aeration and drainage.

Composition of bark and wood of southern hardwoods (see sections 6-1 and 13-5) are compared with that of peat (approximated from Feustel and Byars (1930), Anderson et al. (1951), Basham and Thompson (1967), and Plaisance and Cailleux (1958)), as follows:

Content	Wood	Bark	Peat
		Percent	
Mineral content	0.4	4–12	4
Organic content			
Carbohydrate	70.7	30–48	70
Lignin (incl. phenolic extractives in bark)	24.4	33–46	18
Extractives	4.5	5–10	8
Mineral plus organic content	100	100	100
Water soluble	2–10	8–16	5.0
Nitrogen	.4	.5	.8
Carbon	50	47–50	43–63

Of the three, bark has the lowest carbohydrate content. The total carbohydrate content of peat (70 percent) is probably comprised of about 4/7 cellulose and hemicellulose and 3/7 other carbohydrates soluble in sulfuric acid or 2 percent hydrochloric acid (Feustel and Byars 1930; Anderson et al. 1951). Peat is more acid than wood, with a pH of about 3.5 to 3.8.

Bark and peat are also very similar in cation exchange capacity (CEC), i.e., the ability to retain nutrients against leaching.

Organic amendments used in container growing—where water loss is rapid—should hold four to five times their dry weight in water. Both bark and peat moss meet this requirement.

The carbon/nitrogen (C/N) ratio should be relatively low, or additional nitrogen must be added to offset that temporarily lost to protoplasm of micro-organisms using the organic matter as a carbon source. These micro-organisms have a C/N ratio of about 10/1. A shortage of nitrogen can limit the rate of decomposition of organic matter. Optimum decomposition in soil usually results when the ratio of carbon to nitrogen is about 20/1 (Bollen and Glennie 1963). Peat-sand combinations, which may have a C/N ratio of 50 or 60 to 1, decompose so slowly that additional nitrogen is usually unnecessary. The C/N ratios of bark-sand combinations are higher, and additional nitrogen is generally required; the added nitrogen becomes available to plants as the bark decomposes. Soils mixed with sawdust require greater additions of nitrogen than those mixed with bark.

The relationships governing nitrogen requirement and rate of decomposition are complex; generally the nitrogen requirement increases with increased rate of decomposition. Decomposition rate is dependent on the organic material (lignin decomposes more slowly than cellulose, for example), soil pH, soil aeration, and soil moisture and temperature. Readers desiring additional information will find Russell (1961, p. 240-250) and Alexander (1967, chapter 9) useful.

Joiner and Conover (1969) conclude that physically bark compares closely with peat moss. The major disadvantage of bark is its high C/N ratio and more rapid rate of decomposition. On the plus side, barks of southern hardwoods do not have high levels of soluble salts—a problem with some peat moss.

Bark and wood fragments—like peat moss—can serve many purposes in horticulture and agriculture, some with minimum preparation, and others after more substantial modification. Some of these uses are described in the following subsections. In most cases, species-specific experimental data relating bark or wood species to crop species are lacking. Generally, soil amendments should have high water-holding capacity and CEC, low soluble salt level and C/N ratio, slow decomposition rate, and uniform particle size.

ROOT-BALL PACKING

Hardwood barks, e.g., red oak sp., white oak, sweetgum, hickory, red maple, elm sp., and black tupelo, can be hogged through a 1-inch screen, aged in piles for perhaps 4 months, and mixed with soil to provide a medium for packing root balls of young trees and ornamental shrubs for nursery storage. The packaged root balls can be held together in preservative-treated burlap sacking or in plastic netting or bags. Data relating health of shrub and tree species in the nursery to bark species used for packing root balls are scarce, however. Harkin and Rowe (1971) note that incorporation of the stringy portion of inner bark or of wood excelsior reduces loss of bark crumbs and soil during planting. Additions of slow-release synthetic fertilizers and lime can be used to increase the keeping time and growth of plants while packaged.

POTTING MEDIUM FOR CONTAINER STOCK

Barks of major southern hardwood species, e.g., red oak sp., white oak, elm sp., ash sp., sweetgum, hickory sp., black tupelo, and red maple can be effectively used as a potting medium and for rooting plant cuttings. Literature relating plant health to bark species used for potting and rooting are scarce. Harkin and Rowe (1971) listed the following plants that grow well on a bark potting medium: pines, firs, junipers, holly, forsythia, rhododendrons, gardenias, azaleas, pieris, camellias, heather, and orchids. Chrysanthemums, poinsettia, geraniums, cyclamens, hydrangeas, lilies, roses, and numerous other plants have also been successfuly grown on soil amended with hardwood bark.

Spomer (1975a) explained that soil in a container (e.g., pot, can, bench, flat, planter) is distinguished from the same soil in a field because it is small in volume and shallow in depth. Smallness limits water and mineral supply to the plant. The effect of shallowness is less obvious; a perched water table forms at the container bottom resulting in a saturated soil and poor soil aeration following irrigation and drainage. Poor aeration causes poor root growth and may kill the plant. The effects of smallness are remedied by frequent irrigation, but that aggravates frequency and duration of poor soil aeration. Composted bark is one coarse textured material that can minimize this problem (other amendments include sand, perlite, gravel, calcined clay, vermiculite, and peat). The amount of amendment required for good growth is usually determined by experiment. Readers interested in a theoretical determination should find useful Spomer's (1973, 1974, 1975bc) work.

Liquid fertilization methods are widely used for soils amended with peat or softwood bark. Gartner et al. (1971) reported that hardwood bark-amended soils require some high-nitrogen, slow-release fertilizer, however. Addition of lime (needed for peat moss mixes) was apparently not needed for satisfactory pH of bark mixes.

Gartner and Williams (1978) obtained good growth with hardwood bark processed in a hammer mill and screened to yield particle size classes as follows: 20-40 percent smaller than 0.03 inch, about 55 percent 0.03 to 0.25 inch, and 10 to 20 percent larger than 0.25 inch. Particles larger than 0.25 inch dry too rapidly, and those smaller than 0.03 inch aerate poorly. Composting of hardwood bark to eliminate phenolic growth inhibitors is necessary when it is used as a growth medium. Gartner and Williams (1978) found no difference between sand and soil for incorporation in a growing mixture. Several commercial growers in Illinois are using their formula for production of their crops:

> "To each cubic yard of 5:1 bark:sand mix, add 6 pounds of ammonium nitrate, 5 pounds of superphosphate, 1 pound of elemental sulfur, and 1 pound of iron sulfate. Mix thoroughly in a drum or rotary mixer. After mixing, stockpile moist (about 80 percent moisture content) for a minimum of 6 weeks."

The nitrogen used during stockpiling offsets decomposition; when the composted mix is applied to the crop it is necessary to further fertilize at every watering, using a complete nutrient solution (20-20-20 analysis of NPK), with about 250 ppm of nitrogen, depending on the crop.

DeCamp (1980) described an industrial operation of Paygro, Inc., South Charleston, Ohio. The company uses inside storage of hardwood bark (75 percent oak) in piles and composting tanks that reduce time for composting to only 10 days in optimum summer weather and 3 weeks in temperatures below 30°F. Prior to composting, 4 lb of nitrogen (in the form of ammonia nitrate and urea) and 0.2 lb of phosphorus (in the form of triple super phosphate) are added to each cubic yard of bark. As the bark—including the foregoing additives—is put into the composting tanks, water is added to bring the moisture content to approximately 60 percent (wet weight basis). After composting, 1 lb of iron sulfate, 1 lb of magnesium sulfate, and 2 lb of sulfur (the latter to control pH) are added to each cubic yard of bark. The material is then stockpiled for 30 days on an outside concrete slab in large windrows. After the stockpiling period the material is ready for sale as a potting medium for container stock. Salts content varies from 0.8 to 1.2 percent and pH from 5.5 to 6.0. In 1981, sales price F.O.B. the South Charleston plant was $18.50/cu yd. DeCamp noted that the principal advantage of the material is pathogen control afforded by hardwood bark to inhibit root rots and parasitic nematodes.

Readers needing further information on hardwood bark utilized in potting mediums are referred to the following articles published since 1972:

Reference	Subject
Morris and Milbocker (1972)	Japanese holly
Scott and Bearce (1972)	Greenhouse pot flower production
Still et al. (1972, 1975)	Chrysanthemums (bark, sawdust)
Szopa et al. (1973)	Chrysanthemums
Hoitink et al. (1975)	Composted bark for control of root rot in ornamentals
Klett, J. E. (1975)	The effects of various sources of N using hardwood bark as a potting growth media. 6 p. Paper presented at The utilization of hardwood residues—a Symp. Champaign, Ill., Oct. 15–17, 1975
Malek and Gartner (1975)	Hardwood bark soil amendment for suppression of plant parasitic nematodes
Daft et al. (1979)	Composted hardwood bark for control of poinsettia crown and root rot
Smith and Treaster (1981)	Hardwood bark for container grown woody ornamentals

MULCH

Mulch is material applied to the surface of a soil to prevent erosion, soil compaction or crusting, evaporation of soil moisture, emergence of weeds, and extreme fluctuations in soil temperature. A good mulch is attractive in appearance, helps the soil absorb moisture, and prevents mud and surface organisms from splashing onto plants during a rain or periods of overhead irrigation.

Both bark and wood of southern hardwoods can be used as mulch, but the two materials differ in some respects. Bark has darker color than wood, and is more pleasing to the eye than a mulch of sawdust or shavings. Bark decomposes in soil more slowly than wood—slowing nitrogen depletion. An advantage in the South is that bark does not attract termites nor provide nutrients to them. Bark is richer in extractives than wood; bark tannins form chelates with heavy metal cations and help retain important minerals in the soil, and they complex with soil nitrogen compounds and prevent their rapid breakdown or elution. Both effects can promote fertility. Also, beneficial effects of bark in depressing soil-borne plant diseases have been observed (Harkin and Rowe 1971).

Van Nierop and White (1958) compared wood-chip and sawdust mulches (two parts hardwood to one part softwood) with mulches of reed-sedge peat and sphagnum peat for application on forest nursery soils in Syracuse, N.Y. They concluded that both wood chips and sawdust were more stable and provided greater soil moisture retention than the two peats; sawdust and wood chips were equally effective in this respect. Soil acidifying effects of the wood—particularly sawdust—were less than commonly supposed. The wood chips and sawdust mulches created conditions favoring a significant increase in the population of earthworms and nematodes.

Strip-mine spoil banks and roadsides.—Sarles and Emanuel (1977a) applied hardwood bark mulch to disturbed sites in West Virginia, including surface-mine spoil banks, earthen dams, and roadsides. They found that a hardwood bark mulch was effective for establishing vegetative cover quickly and controlling erosion when applied with recommended amounts of lime, seed, and fertilizer. The hardwood barks, including oak bark, enhanced seed germination and development. They recommended that 30 cubic yards of bark mulch be applied per acre on north and east slopes that are 2:1 or less. Fifty cubic yards per acre are needed on slopes steeper than 2:1, on slopes that face south and west, and for overwinter protection of disturbed sites. Machine application of the bark mulch requires uniformity of particle size and freedom from dust; they recommend that bark residue be shredded and screened to eliminate fine particles.

Emanuel (1976) found that hardwood bark fines smaller than 1/10-inch and bark fiber can be effectively used as mulch on disturbed sites if applied in a water-borne mixture of mulch, seed, and fertilizer; the hydromulch is applied at 1,500 pounds per acre (20 percent moisture basis).

Graves and Carpenter (1980) found that application per acre of 35 tons of hardwood bark mixed with 2.5 tons of chicken manure, or 35 tons of a 1:1 mixture of hardwood bark and composted garbage-manure was superior to water-borne fiber mulches in establishing permanent legume and grass vegetation on drastically disturbed strip-mined land in Kentucky. This was primarily attributed to the rapid establishment of legumes in bark-based mulches; establishment of grasses was faster in water-based fiber mulches, but no legumes competed with the grass so established. Heavy-seeded tree species (e.g., the oaks) and Virginia and loblolly pines were successfully direct-seeded on surface-mine spoils mulched with bark; other pines responded adversely to the bark. Survival of most bare-root and containerized seedlings was increased by a bark mulch; apparently the mulch greatly reduced seasonal moisture stresses.

Application equipment.—Bark mulches are most easily applied with blowers and hydromulch machines. Readers interested in the technique are referred to Emanuel (1971), Knutson (1975), Sarles (1975), Sarles and Emanuel (1977b), Smith and Coulter (1980), and Allison.[7]

COMPOST FOR SOIL AMENDMENTS

At some locations in the South there are sites where organic materials in soils are depleted and where crop residues are inadequate to replenish organic materials. Throughout the South, however, there are abundant supplies of organic material in the form of hardwood bark, whole-tree chips, and sawdust. What is required and what are the problems of using the hardwood residues as soil amendments?

Lunt (1955) summarized 5 years of experimentation introducing hardwood chips (including oak and hickory) into container-soils and field plots. He found that woodchips (or sawdust) had no appreciable effect on soil acidity nor were they toxic to plants aside from temporary nitrogen deficiency. Chips had a generally favorable effect on soil structure, and organic matter content. When fresh, woodchips almost invariably reduced first crop growth. When supplemented with sufficient nitrogen or when composted before application, chips did not decrease first crop yields and generally increased yields of succeeding crops. Woodchips appeared more effective on sandy soils than on loams although very coarse-textured soils sometimes became excessively loose and open the first year or two unless composted. Birch chips decomposed more rapidly than either oak or pine and would require the most nitrogen to prevent deficiencies. Pine chips decomposed most slowly, required the least nitrogen, and were generally most effective in improving the soil.

Lunt's observations and those of many others indicate the desirability of composting bark and wood residues before their introduction as soil amendments. The literature (see the publication *Compost Science*) contains much data on the process. Apparently, however, the economies of the procedures have not fostered their widespread application on an industrial scale.

Processes requiring purchased ammonium nitrate and superphosphate as described by Gartner and Williams (1978)—see POTTING MEDIUM FOR CONTAINER STOCK, or poultry manure (Mater 1977a), or anhydrous ammonia and inoculum with actively fermenting sawdust containing abundant fungus mycelia (Wilde 1958) have evidently not proven economically viable for large-scale agricultural use. Needed is a large-scale process that will convert whole-tree chips of mixed hardwood species into a cheap soil amendment for widespread agricultural use. The operation described by DeCamp (1980) successfully markets a hardwood bark compost for potting container stock but not for broad-scale use to improve agricultural land.

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[7] Allison, R. C. 1975. Use of hardwood bark for highway erosion control and slope stabilization in the southern states. Paper presented at the symposium on "The utilization of hardwood residues." Univ. Ill., Urbana, Ill., Oct. 15–17, 1975. 17 p.

To put the problem in perspective, an acre foot of hardwood whole-tree chips or bark, at 60-percent moisture content for composting as recommended by Cappaert et al. (1975), weights 300 to 500 tons. It is difficult to visualize processes whereby whole-tree chips could be harvested, composted, and incorporated in sandy soils deficient in organic materials at a price less than $20 per ton (1981 basis), even if a low-cost natural source of nitrogen was available. Dunn and Emery (1959) found that chopped green vegetation (fresh grass silage), and also poultry manure, were very effective aids to composting sawdust. It is likely that manipulation of the amount of green vegetation incorporated with whole-tree chips could produce a useful compost.

Use of such compost would appear cost-restricted, however, to intensively improved areas such as golf greens and fairways, lawns, recreation grounds, or those requiring erosion control. A 3-inch layer of composted bark or whole-tree chips incorporated into the top 6 inches of soil would likely cost $1,500/acre or more.

Once well developed for special areas, such soil rehabilitation procedures could perhaps spread to intensively cultivated lands for truck crops, plant nurseries, and other specialized crops. Block and Rao (1962), for example, found oak sawdust promising for the growing of mushrooms.

Readers interested in the design of bins, pits, or piles for composting hardwood bark or whole-tree chips, and a description of material-handling procedures are referred to Wilde (1958), Dunn and Emery (1959), Krause (1962), Mater (1977a), Leonard and Fay (1978), Gartner and Williams (1978), and DeCamp (1980).

NUTRIENTS IN ASH

Since much hardwood bark will be burned by the forest products industry to produce process heat and energy, ash from the bark will be disposed of in large quantities. Host and Pfenninger (1978) suggest that ash from bark and wood could serve as a low-grade, slow-release fertilizer or be added to pulverized bark to physically improve heavy clay soils. The alkalinity of ash suggests its use to neutralize acid soil. It also contains mineral elements essential for plant growth (table [illegible]-19). Two-thirds or more of bark ash, by weight, is silicon dioxide (SiO_2) and calcium oxide (CaO).

Wood ash may contain heavy metals controlled by the Resource Conservation and Recovery Act of 1976,[8] i.e., barium, silver, selenium, arsenic, lead, and chromium. The heavy metals content of wood ash is highly variable, so generalizations are difficult; Carson and Weeter (1980) found that an ash from southern hardwoods had a chromium content greater than the proposed standard.[8]

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[8] Proposed regulations, Resource Conservation and Recovery Act of 1976, Federal Register, May 19, 1980.

GROUND COVER FOR LANDSCAPING EFFECTS

Roth[9] studied the suitability of hardwood bark for camping pads and picnic areas. He found that it provided a durable soft; level, dry tent foundation and that it was clean, had a pleasant odor, remained usable in wet weather, blended well with the landscape, and provided an easily located and identifiable camp spot. Medium- and coarse-grade bark fragments were better than finely ground material. A 4-inch depth was best, but a 2-inch depth was also satisfactory.

Holmes et al. (1973) found that a hardwood bark surface provided protection for a simulated trail as evidenced by increased soil moisture percentage and reduced bulk density as compared to the control surface. A 4-inch thickness of medium-grade bark provided more site protection than 2-inch thickness. A medium grade bark (45.5 percent of pieces smaller than ¼-inch and only 3 percent as large as 2 inches in diameter) was superior to a coarse grade (42.5 percent of pieces smaller than ¼-inch and 6 percent as large as 2 inches in diameter).

Decorative landscape effects can be achieved by use of large-size bark chunks. Based on experience with bark of western conifers, only logs with bark thickness of an inch or more will yield particles of sufficient size for the best decorative ground cover. Few small hardwoods have such thick bark (see figs. 13-59 through 13-64).

POULTRY LITTER

Allison and Jordan (1973) concluded that a good poultry litter must absorb moisture from bird droppings and dry quickly. It should be dust-free, even after use. Not more than 10 or 20 percent of the litter should be smaller than 1/16-inch in length and the largest particles should not exceed 1 inch. Particles should resist matting and be flake-like, light, buoyant, and of low bulk density. Soft compressible material lacking sharp splinters is best, and the material should be free of pathogenic organisms. It should be available during all months of the year at a reasonable price ($20 to $40 per ton delivered, 1963), be easy to handle, be non-toxic and non-staining, and permit use as a fertilizer after use as litter.

Dry planer shavings have been the primary source of litter in sheds where chickens are raised, but in many areas such shavings are unobtainable at an acceptable price. Hardwood bark, however, is frequently available and can serve well. Fresh hardwood bark is typically lower in moisture content (tables 13-30 and 13-32) than green softwood planer shavings and therefore needs less drying to be at optimum moisture content (50 percent or below). Allison and Jordan (1973) noted that brooder heat can be used to dry spread bark litter for a day or two before placing birds in it.

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[9] Roth, P. L. 1975. Shredded hardwood bark—a promising material for recreational use. Paper presented at the symposium on "The utilization of hardwood residues." Univ. Ill., Urbana, Ill., Oct. 15–17, 1975. 11 p.

Allison and Jordan (1973) found that coarse-textured barks hammermilled to pass a ⅜- to ½-inch screen yielded good poultry litter, but advised against using the stringy bark of elm and yellow-poplar. Labosky et al. (1977a) tested mixed hardwood bark (50 percent yellow-poplar, 25 percent southern red oak, and 25 percent black tupelo) with good results in comparison to litters including dry shortleaf pine planer shavings mixed with sawdust.

Labosky et al. (1977a) concluded that fresh hardwood bark, as it came from a rosser-head debarker or after hammermilling and screening, can be a satisfactory poultry litter. Birds raised on bark litter showed no significant difference in broiler breast blisters, swollen hock joints, or bird mortality from controls; growth and feed conversions were normal. Hammermilled hardwood bark tended to cake more than unaltered fresh bark. Reused bark litters disintegrated more slowly than controls, reducing litter contamination in feeders and water dispensers. They found that, with proper management bark litter can be successively reused for as many as five broods of broilers with no apparent adverse effects on broiler health and quality.

Labosky et al. (1977b) concluded that, from a nutritive standpoint, bark poultry litters are potentially useful as a ruminant feed. Hardwood bark litter appeared to ensile better and to be more digestible and possibly more nutritious than softwood bark or softwood planer-shaving litters.

ANIMAL BEDDING

Larsen et al.[10] found that cows in a free-stall barn, but under complete confinement, preferred—in the order named—stalls with dirt floors and deep bedding over cement-floored stalls (with bedding), rubber-mat based stalls, carpeted stalls, or cement stalls without bedding. Of the bedding tried (chopped straw, dry sawdust, shredded bark mixed with mill-run sawdust), the bark-sawdust mix performed best, requiring least volume and affording best cleanliness with least labor; animals using this bedding were free of leg bruises and injuries and were very clean. Amounts required per heifer day were as follows (dry basis):

Animal age	Weight of bedding/day
	Pounds
2 months to 1 year	1.5 to 2.2
1 year to 2 years	3 to 4

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[10] Larsen, H. J., G. H. Tenpas, D. A. Schlough, and C. Cramer. 1976. Investigations of bedding materials, cleaning time, stall selection, herd health, and cleanliness for stanchion and free stall housing. Depts. Dairy Sci., Agronomy, and Exp. Farms 1976 Rep. 13 p. Univ. Wisconsin, Madison.

McGovern et al. (1977) found that aspen bark (*Populus tremuloides* Michx.) from a rosser-head debarker was suitable for use as livestock bedding without further processing. If shredded in a hog with swinging hammers (fig. 18-277), the resultant low-bulk-density material was highly suitable for livestock bedding at a low rate of application. Green bark residue performed better than dry, which packed poorly and was dusty. The bark bedding received full animal acceptance. When the spent bedding material was applied to corn fields, manure in the bedding more than offset the nitrogen-depleting effect of the bark alone.

MAKING AND MARKETING BARK PRODUCTS

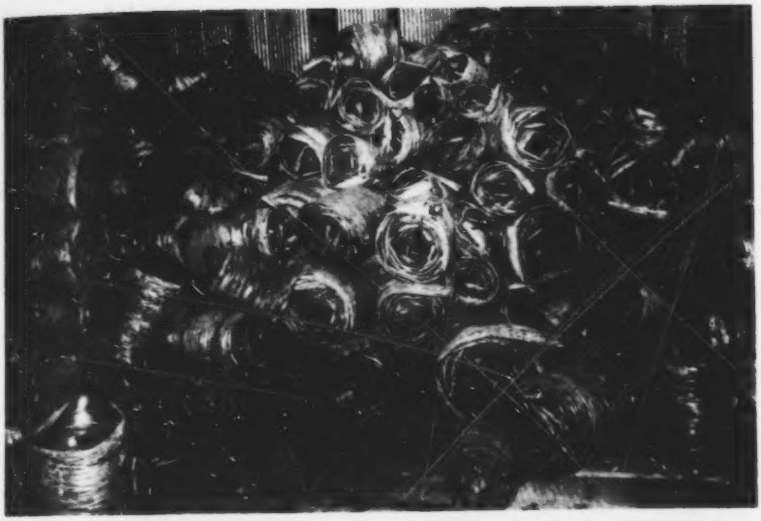
Following are references related to the manufacture and marketing of hardwood bark products:

Reference	Subject
Mater et al. (1968)	Making and selling bark products
Allison (1971)	Oak bark mulch manufacture
Mater (1972; 1977b)	Techniques of processing and utilizing bark
Fisher (1974)	Bagging technique
Mater (1974)	Technological options and materials handling
Wartluft (1974b)	Baling technique
Emanuel (1978)	Screening technique related to species and particle size
Griffin (1979)	Manufacture and marketing

13-8 INDUSTRIAL UTILIZATION

Mill operators need profitable large-scale processes for the utilization of hardwood bark residues, but such processes—with the exception of combustion, are few. One small-scale use is for furniture seats and backs of rustic furniture. For this purpose bark of pignut hickory is purchased by the hundred square feet of surface measure, delivered, and stored in rolls (fig. 13-81 top). In making strips for furniture barks and seats (fig. 13-81 bottom) craftsmen soak the bark in warm water, cut it longitudinally to the width desired, and then split the inner bark of these strips away from the outer bark. Chair seats and backs woven from such inner bark are extremely durable and acquire an attractive patina after long use. Tests of a few pieces of inner bark of pignut hickory equilibrated to 12 percent moisture content indicated a tensile strength of about 12,400 psi and modulus of elasticity of about 242,500 psi.

Fuel, fiber, and chemical feed stock appear to be the industrial products having most promise for large-scale operations utilizing hardwood bark.



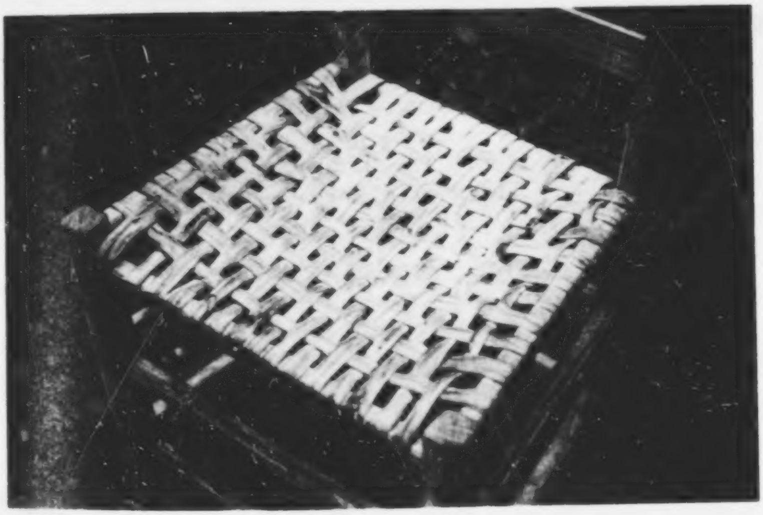


Figure 13-81.—(Top) Pignut hickory bark, purchased by surface measure and stored in rolls for use in chair seats and backs. (Photo from Purdue A.E.S.) (Bottom) Chair seat woven from strips of the inner bark of hickory.

FUEL

Of non-agricultural industrial uses, fuel for forest-industry plants will likely account for most hardwood bark utilized. Even in 1973, when fossil-fuel prices were low, the volume burned was several times that of all other uses combined. Welch and Bellamy (1976) surveyed primary wood-using plants in Florida, North Carolina, and South Carolina in 1973 and Georgia in 1974 and found hardwood bark use in these states, as follows:

Use	Annual volume
	M cu ft
Industrial fuel	29,534
Fiber products	1,226
Domestic fuel	665
Charcoal	301
Particleboard	8
Miscellaneous (including agriculture)	2,367
Not used	18,082

Heats of combustion of southern hardwood barks are given in tables 9-12, 13-44, 13-45, 13-46, and in related discussion. Moisture contents are given in section 13-4. Combustion of bark, charcoal manufacture, other processes by which energy is produced from bark, and equipment required are described in chapter 26. Sections 28-1, 28-5, 28-6, 28-10, 28-20, and 28-33 summarize the eonomics of using hardwood residue as an energy source.

As the cost of fossil fuels continues to rise, it seems likely that use of bark for fuel will continue to intensify. Its value as fuel will inhibit alternate uses except for high-value products. Some product possibilities include deflocculants, filter mediums, adhesives, and fiber products.

OIL INDUSTRY USES

While current use of hardwood bark by the oil industry is limited, it is possible that some uses can be developed. For example, bark tannins from western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) find a large market as clay deflocculants that control the viscosity and gel strength of drilling muds (Hergert et al. 1965). Also, bark fibers can be added to drilling muds to reduce circulation losses. Haynes (1968) briefly described the operation of U.S. Plywood-Champion Papers, Inc. at Pasadena, Tex., which processes bark (40 percent hardwood and 60 percent southern pine) into products including an oil-well mud additive. Miller and Van Beckum's (1960) review of the uses and sources of bark products for oil well drilling should be helpful to those considering this market.

Weldon (1970) has demonstrated that southern pine bark can be used to scavenge oil spills from the surface of salt water. Best results were obtained by depositing loose bark particles, measuring 1 to 2 mm in size, directly on the oil slick; the bark took up the oil in a matter of seconds but absorbed little water. When the oily bark was skimmed from the surface, the water was left free of oil. While not described in the literature, some hardwood barks light enough to float would probably be equally effective.

FILTERS AND HEAVY-METAL SCAVENGERS

Biofilter.—Alestalo and Koistinen (1975) found that a bark biofilter (fig. 13-82) can be used to purify malodorous pulpmill condensates. The effectiveness of the process depends on the ability of the microorganisms living on the bark to oxidize the malodorous sulfur compounds to odorless forms and to reduce biological oxygen demand (BOD) primarily by oxidizing methanol. To intensify this oxidation by microorganisms, the bark medium is preimpregnated with nutrients. The oxygen necessary for the process blows through the biofilter from bottom to top countercurrent to the flow of trickling condensate. Alestalo and Koistinen found that the efficiency of the bark biofilter in the oxidation of malodorous sulfur compounds (hydrogen sulfide, methyl mercaptan, dimethyl sulfide, and dimethyl disulfide) is 90 to 100 percent, and in oxidation of methanol 40 to 80 percent.

Lightsey and Mitchell (1975) and Lightsey et al. (1976) found that 6-foot-deep bark filters (8 percent hardwood and 92 percent southern pine in as-received condition from drum debarkers) are effective in removing settleable matter and BOD from the liquid fraction of sludge discharged from a pulpmill primary classifier. The settleable matter is converted to a dewatered sludge at the filter face and BOD removed in the liquid is up to 95 percent. Maximum chemical oxygen demand (COD) removal was 42 percent. The nitrogen content of the bark filter medium increased significantly after 2 months of use, enhancing its utility for soil amendment.

Scavengers of heavy metals.—Toxic heavy metal ions—especially lead, cadmium, and zinc—in industrial waste waters can be adequately sorbed from solution by synthetic ion-exchange resins, but they are usually expensive and costly to regenerate. Randall (1977) found that barks of several tree species are effective ion-exchange substrates for the removal of these heavy metal ions. Of the barks tested, redwood (*Sequoia sempervirens* (D. Don). Endl.) was the most effective. Data on the few southern hardwoods that were tested indicated (table 13-47) some promise. The binding of heavy-metal ions on bark is pH-dependent, probably partly because tannins in the bark act as weak ion-exhangers, releasing two hydrogen ions into solution for each divalent metal ion bound to the solid.

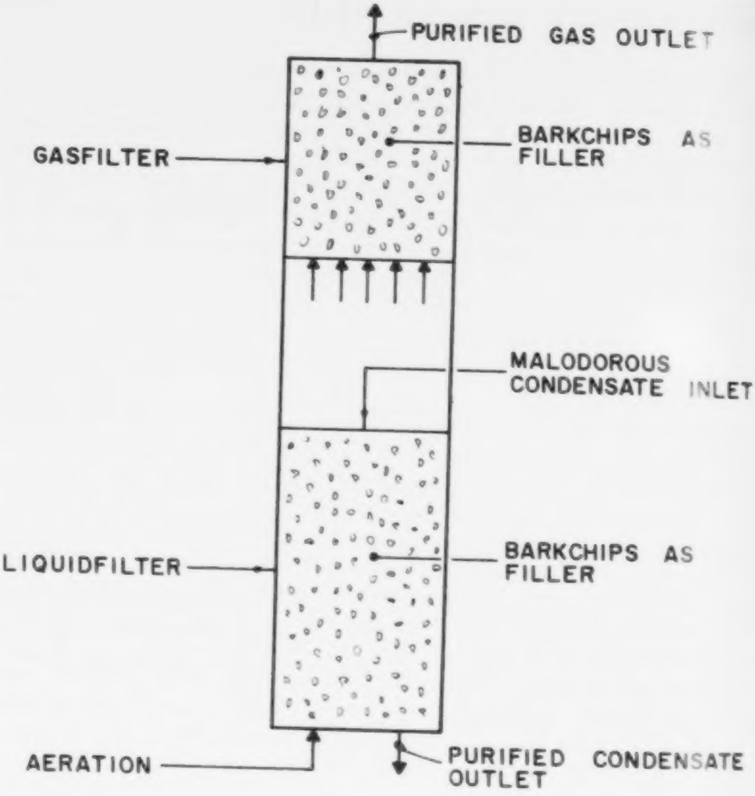

PURIFIED GAS OUTLET
BARKCHIPS AS FILLER
GASFILTER
MALODOROUS CONDENSATE INLET
BARKCHIPS AS FILLER
LIQUIDFILTER
AERATION
PURIFIED CONDENSATE OUTLET

Figure 13-82.—Design of bark biofilter. (Drawing after Alestalo and Koistinen 1975.)

TABLE 13-47—*Affinity of barks of five hardwoods and redwood (Sequoia sempervirens (D. Don) Endl.) for seven heavy metal ions* (Randall 1977)

Bark species	Affinity[1] for:						
	Cd	Cu	Pb	Ni	Zn	Ca	Mg
Ash, white	+ +	P	+ +	+	—	—	—
Elm, American	—	+	—	—	+	—	—
Maple, red	—	+ +	+ +	+ +	+	—	—
Oak, cherrybark	P	P	+ +	P	P	P	P
Sweetgum	+ +	—	+ +	—	—	—	—
Redwood	+ +	+ +	+ +	+	+ +	+ +	+

[1] + + = promising; + = possible; P = poor sorption; — = not tested.

Disposal of barks used for scavenging heavy-metal ions might present a problem. If burned, resulting ash might have unusually high content of toxic metals. A preferable method is removal of the heavy metals and reuse of the bark. All heavy metals tested by Randall (1977) and Randall et al. (1974) can be quantitatively desorbed from the bark substrate with 0.1 N HCl. This puts the metal ions in solution again but at much higher concentration than in the original waste; at concentrations of 5 to 20,000 ppm, the heavy metal ions can be precipitated by addition of chemicals or by pH change. The eluted bark can be used many times.

CHEMICAL UTILIZATION

The chemical constituents of bark are briefly described in sections 13-5 and 6-6. While the literature contains many publications on bark chemistry, information specific to southern hardwoods is meager.

During the 1920's use of chestnut oak bark for extraction of tannin for the leather industry was extensive, but labor intensive. It, along with wood of American chestnut (*Castanea dentata* (March.) Borkh.) cut for the same purpose, was the primary source of income to many small landholders throughout the Appalachians and Piedmont. By the end of World War II, however, tannin from this source was no longer economically competitive.

Development of other major chemical uses for barks of southern hardwoods—except as paper—will likely be delayed until a better understanding of their chemical components is achieved.

PAPER

Southern hardwood barks, unlike barks of southern pine, contain fibers, the percentage varying widely with species. Barks of hickory, ash, elm, red maple, and yellow-poplar, for example, have high fiber content, while those of southern red oak and white oak have little. Inner bark has a significantly higher fiber content than outer bark.

Einspahr and Harder (1976) reported that barks of white, northern red, and southern red oaks kraft pulped to a kappa number of 8 to 12 yielded 28 to 37 percent pulp of which only 3 to 5 percent was usable fiber retained on 60- and 100-mesh screens; most came from the inner bark.

Bark of hickory appears most promising because it has thick secondary phloem containing a high proportion of phloem fibers. The secondary wall of a hickory phloem fiber is thinner than that of other species, and the fibers have a relatively large lumen (fig. 13-23 right). These features of phloem fibers generally will enable them to collapse and become flexible; therefore, better fiber-to-fiber contact can be developed. Moreover, the low lignin content of these fibers is of economic significance as pulping costs would be reduced.

Because the southern pulp industry perceives a need to obtain more fiber from each acre of forest harvested, increased emphasis is being placed on pulping bark rather than debarking bolts or segregating bark from the wood in whole-tree-chip mixtures. The fibrous elements of bark are illustrated in figures 13-9 and 13-21 through 13-25, and further described by tables 13-1 through 13-3.

Harder et al. (1978) concluded that phloem fibers, if dispersed, can provide usable pulp and increase yield per cord. Thin-walled, sieve-tube elements can be used as fillers, thereby increasing yield per cord, but it is doubtful that they contribute usefully to paper mechanical properties. Table 13-48 summarizes their evaluation of solids yield and percentage of usable bark fiber in a variety of hardwood barks pulped in the laboratory. Post oak and black willow had very high solids yield (46.2 and 40.0 percent), and the average for all of the hardwoods studied was 33.4 percent. Black willow, white ash, and shagbark hickory were species with greatest amounts of usable fiber (15 to 21 percent) and with few or no sclereids in the bark. Sycamore, American beech, and red alder contain little or no fiber in the bark.

Following are accounts, beginning in 1950, of various laboratory and mill trials of pulping bark-wood mixtures of southern hardwood species.

Keller (1950) compared neutral sulfite chemical pulps made from bark-free pignut hickory chips with pulps containing 25 percent bark and 100 percent bark. Pulp yields were 76 percent for the wood, 72 percent for the wood and bark, and 52 percent for bark alone. The strengths of pulps made with hickory wood plus bark were only slightly lower than strengths of those made from wood alone. A pulp prepared entirely from bark had practically no folding endurance, however. Incorporation of bark did not alter sheet density greatly.

TABLE 13-48—*Yield and fiber and sclereid content of 24 hardwood pulps* (Harder et al. 1978)[1,2]

Species	Solids yield	Total fiber	Usable bark fiber	Total sclereids	Sclereids or phellem cells remaining
				---------*Percent* ---------	
HARDWOODS COMMONLY FOUND WHERE SOUTHERN PINES GROW					
Ash, green	38.0	15	13	4	<1
Ash, white	35.7	18	16	1	0
Hickory, shagbark	28.3	15	15	0	0
Maple, red	32.0	17	12	5	<1
Oak, black	31.4	5	5	9	0
Oak, northern red	28.4	5	5	13	<1
Oak, post	46.2	8	4	8	0
Oak, southern red	30.7	4	4	18	0
Oak, white (from South)	36.6	4	3	23	0
Oak, white (from North)	35.4	4	3	9	0
Sweetgum	34.9	7	5	3	0
Tupelo, black	31.4	7	6	<1	0
Yellow-poplar	32.3	15	13	1	0
OTHER HARDWOODS					
Alder red (*Alnus rubra* Bong.)	27.0	0	0	11	0
Aspen, quaking (*Populus tremuloides* Michx.)	33.8	8	8	13	1
Beech, American (*Fagus grandifolia* Ehrh.)	37.0	<1	<1	24	0
Birch, white (*Betula papyrifera* Marsh.)	36.3	0	0	22	<1
Cottonwood, eastern (*Populus deltoides* Bartr. ex Marsh.)	35.4	10	9	<1	<0.1
Cottonwood, northern black (*Populus trichocarpa* Torr. & Gray)	26.0	12	12	<1	0
Maple, silver (*Acer saccharinum* L.)	32.0	7	6	17	2
Maple, sugar (*Acer saccharum* Marsh.)	33.9	3	3	16	<1
Oak, pin (*Quercus palustris* Muenchh.)	26.5	2	2	10	0
Sycamore (*Platanus occidentalis* L.)	31.4	0	0	0	0
Willow, black (*Salix nigra* Marsh.)	40.0	23	21	1	<1

[1] Micropulped in the laboratory by the method of Thode et al. (1961).

[2] Total fiber and sclereids are the fiber and sclereids retained on all screens plus the material passing through the 200-mesh screen. Usable bark fiber and sclereids remaining are the fibers and sclereids retained on 60- and 100-mesh screens. Percentages are based on the amounts in the total bark solids.

Brown (1956) made bleachable and semichemical grade pulps of mixtures of white and northern red oak chips containing up to 24 percent bark by weight. He found that the presence of bark caused: (1) a decrease in yield of pulp obtained from a digester charge but an increase in yield of pulp on an unpeeled pulpwood basis; (2) a decrease in pulp brightness; and (3) a decrease in the strength properties of the pulp. The chemical consumed in pulping oak bark was about the same as that consumed in pulping the wood. Sulphate pulping of the bark alone was found to be impractical because of the low yield and poor quality of the pulp obtained. The strength of a bleachable sulphate pulp made from an oak mixture containing 16 percent of bark was increased by centrifugal cleaning, and became approximately the same as that of a cleaned pulp prepared under similar conditions from peeled wood. There was very little, if any, difference in appearance between these two pulps after they were bleached by a multistage process to a brightness of 83 percent. The results of these experiments showed that about 2 percent more bleached, cleaned fiber could be obtained from rough pulpwood containing 16 percent of bark by not removing the bark before pulping. The presence of bark during the sulphate semichemical pulping tests produced pulps so weak that they probably would have no use.

Powell et al. (1975) compared bleached kraft pulps made from whole-tree southern hardwood chips containing 18 percent bark with pulps made from bark-free hardwoods. They found that bleached pulp of high quality and normal dirt level can be obtained from hardwood whole-tree chips if the unbleached permanganate number (a statistic proportional to lignin content) is reduced below normal levels. Even though whole-tree chips did not require more active alkali than bark-free chips to reach a given permanganate number, the caustic requirement for an equivalent tonnage of pulp from whole-tree chips was substantially higher than that from bark-free chips because of lower yields and the lower-than-normal permanganate number required to control dirt.

Chao (1976) concluded from laboratory and mill tests that a 25-percent addition of whole-tree chips of mixed hardwoods from North Louisiana to the regularly used debarked hardwood chips caused no significant difference in chemical composition by the neutral sulfite semichemical (NSSC) process, nor were yield and important mechanical properties of resultant corrugating medium changed; the corrugating medium was somewhat darkened, however, by inclusion of bark on the whole-tree chips.

Einspahr et al. (1979), kraft pulping (microdigester) shagbark hickory chip mixtures containing various levels of bark, found that yields decreased with increasing levels of bark, with yield from bark being about 25 percent that from wood. Using chips containing 15 percent bark resulted in a reduction in pulp yield from 51.8 to 47.0 percent. Pulp freeness was generally lower, and burst strength, fold, and tensile energy absorption increased with increasing bark levels. Tear was greatest at 15 percent bark, and was only 8 to 16 percent lower than that of the wood-only pulp at 40 percent bark content.

Einspahr and Harder (1980) suggest that whole-tree hardwood chips be kept as dry as possible and that mechanical action (e.g., a hammermill) can break up the fiber-poor outer bark into small, easily screened out pieces leaving the fiber-rich inner bark to be pulped. They concluded that under most circumstances, the presence of either bark or branchwood in pulp chips decreases pulp yield and strength. They noted that for sweetgum, black tupelo, and the oaks, which contain 3 to 6 percent usable bark fibers (table 13-48) kraft yields from bark can be expected to be about 17 percent of the wood-only yield. Inclusion of 10-percent bark of these species can be expected to decrease kraft yields from 50 percent to about 46 percent. Because of the relatively small amount of bark fiber and the retaining of some thin-walled bark cells, sheet strength values of centrifugally cleaned pulps should not differ greatly from those for bark-free chips. Mechanical treatment and subsequent screening of chips of these species can be expected to result in bark levels lower than 10 percent, a higher percentage of fiberlike elements, a smaller decrease in pulp yield, and no change in pulp strength (Einspahr and Harder 1980).

FIBERBOARD AND PARTICLEBOARD

Fiberboards.—When bark is added to pulp chips, fiberboard pulp yield is usually lower than when only bark-free wood is used because most barks have higher percentages of water soluble extractives and amorphous material, some of which pass through the sheet-forming screen during wet-process forming. Large quantities of whole-tree chips of southern hardwoods of mixed species are, however, routinely converted to fiberboard at a major wet-process manufacturing facility in Mississippi.

It is possible to make a low-strength fiberboard entirely from hardwood bark. Chow (1976) utilized bark of red oak sp. and white oak to make urea-formaldehyde-bonded board from airdry bark fragments defiberized in a double-disk, steam-pressurized (50 psi) attrition mill with plate spacing of 0.060 inch and 2-minute retention time. Table 13-49 summarizes board properties resulting. Bending strength of bark boards made from such disk-refined material was greater than the strength of those made from comparable bark fragments hammermilled through a ½-inch screen into particles.

Chow (1979, 1980) also made phenol-formaldehyde-bonded boards of northern red oak bark defibrated on a double-disk refiner and obtained properties similar to the U-F boards described by table 13-49.

Particleboards.—Bark fragments of southern hardwoods can be hammermilled and bonded with urea-formaldehyde or phenol-formaldehyde into boards of low strength (Murphey and Rishel 1969). If phenol-formaldehyde-bonded bark boards are impregnated with methyl-methacrylate-type polymers or epoxy-type polymers, major mechanical properties can be increased several-fold (Blankenhorn et al. 1977).

Using hammermilled air-dry bark fragments of red oak sp. and white oak, Chow (1976) made bark boards with modulus of rupture values of 600 to 1,000 psi, modulus of elasticity of 97,500 to 163,000 psi, and linear expansion values (50 to 90 percent relative humidity) of about ½-percent (table 13-49).

TABLE 13-49—*Average properties of ⅝-inch-thick boards made at three resin contents from bark of red oak sp. and white oak disk-defibrated or hammermilled through a ½-inch screen* (Chow 1976)[1]

Species and property	Fiberboard of disk-refined particles at three percentages of resin content[2]			Particleboard of hammermilled particles at three percentages of resin content[2]		
	5.0	7.5	10.0	5.0	7.5	10.0
Red oak sp.						
Modulus of rupture, psi[3]	1,300	1,400	1,500	600	800	1,000
Modulus of elasticity, psi[3]	166,000	156,500	181,500	97,500	131,000	163,000
Internal bond strength, psi[4]	139	146	162	159	190	290
Tension parallel to face, psi[3]	680	690	700	340	460	580
Linear expansion (50 to 90 percent RH), percent[5]	.555	.565	.560	.680	.585	.460
White oak						
Modulus of rupture, psi[3]	900	1,200	1,600	800	1,200	1,350
Modulus of elasticity, psi[3]	139,500	174,000	234,500	101,500	162,500	185,000
Internal bond strength, psi[4]	75	105	123	125	160	176
Tension parallel to face, psi[3]	520	650	910	540	550	700
Linear expansion (50 to 90 percent RH), percent[5]	.400	.360	.360	.410	.380	.415

[1] All values adjusted to a density of 44 lb/cu ft based on ovendry weight.

[2] Urea-formaldehyde resin solids as a percent of ovendry board weight.

[3] Each value is average of six tests.

[4] Each value is average of 10 tests.

[5] Each value is average of two measurements.

Rishel et al. (1980) hot-molded bark under pressure, bonded with 6-percent by weight of powdered phenol-formaldehyde resin, into rectangular specimens 0.25, .50, .75, and 1.00 inch square by a length equal to 20 times thickness. The bark was obtained from a rosser-head debarking machine, kiln-dried to about 5 percent moisture content, and hammermilled to pass an 0.25-inch screen but be retained on an 0.06-inch screen. When loaded in bending, modulus of rupture varied with species from 600 to 966 psi and modulus of elasticity varied from 19,200 to 48,500 psi (table 13-50).

Koch and Hall (1974) and Hall (1974) made experimental barkboards for use as horticultural growth-media cubes intended to compete with peat cubes. Hardwood bark (red oak sp., soft maple, and black birch from a West Virginia sawmill equipped with a rosser-head debarker was airdried and hammermilled through a ¼-inch screen before pressing. When hot pressing without an adhesive binder, they found that press temperature should be about 400°F, press time 10 to 15 minutes, and board density in excess of 50 lb/cu ft to obtain structural integrity. Addition of corn starch as a binder and pressing at 250°F made a board suitable for planting containers or growth-media cubes.

As with wood particles (fig. 24-63), it is possible to make boards and molded products from bark particles and polyurethane foamed resins (World Wood 1977). Galezewski (1977) described an alternative technique calling for mechanically foaming polyvinyl acetate emulsions with hammermilled, airdried red oak sp. bark, pouring the foamed mixture into an aluminum mold, and drying the wet material in an oven. The resulting panel-like material contains from 15 to 26 percent binder by weight, and has a density of 0.3 to 0.5 g/cm^3. Modulus of rupture is low—140 to 409 psi.

TABLE 13-50—*Average flexural properties of bark boards 0.25- to 1.00-inch thick of six hardwood species* (Rishel et al. 1980)[1,2]

Species	MOE	MOR	Density
	psi		*lb/cu ft*
Yellow-poplar	48,500	853	48.4
Oak, northern red	48,400	819	47.6
Cherry, black[3]	31,300	966	46.4
Soft maple[4]	29,100	838	44.8
White oak	23,500	743	42.4
Beech[5]	19,200	600	44.8

[1] Bonded with 6-percent (by weight) of powdered phenol-formaldehyde resin.

[2] Particles were from a rosser-head debarker, dried, and hammermilled to pass an 0.25-inch screen and be retained on an 0.06-inch screen.

[3] *Prunus serotina* Ehrh.

[4] *Acer* sp.

[5] *Fagus grandifolia* Ehrh.

13-9 LITERATURE CITED

Alestalo, A., and O. Koistinen. 1975. On the possibilities of using bark during and after biological conversion. *In* Proceedings of the Eighth Cellulose Conference, I, Wood Chemicals—A future challenge. (T. E. Timell, Ed.) New York, N.Y.: John Wiley & Sons. p. 355-362.

Alexander, M. 1967. Introduction to soil microbiology. 472 p. N.Y.: John Wiley and Sons, Inc.

Allison, R. C. 1971. Utilization of oak residues. *In* Oak Symp. Proc., p. 111-117. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Allison, R. C. and H. C. Jordan. 1973. Criteria and evaluation of hardwood bark as a poultry litter. For. Prod. J. 23(8):46-48.

Anderson, M. S., S. F. Blake, and A. L. Mehring. 1951. Peat and muck in agriculture. U.S. Dept. Agric. Circ. 888. 31pp. Washington, D.C.

Anderson, B. J., and R. F. Evert. 1965. Some aspects of phloem development in *Quercus alba*. (Abstr.) Amer. J. Bot. 52(6, Part 2):627.

Artschwager, E. 1950. The time factor in the differentiation of secondary xylem and phloem in pecan. Amer. J. Bot. 37:15-24.

Baldwin, R. C., W. K. Murphey, and P. R. Blankenhorn. 1974. Scanning electron microscope observation of rate carbonized hardwood bark and bark board. Wood Sci. 6:231-236.

Basham, B. M., and W. S. Thompson. 1967. An economic study of the production and use of sawdust and bark as mulches and soil amendments for horticultural and agricultural purposes. Miss. For. Prod. Util. Lab. Inform. Ser. 6, 27 p. State College.

Binotto, A. P. and W. K. Murphey. 1975. Season and height variation in extractives and cell wall components of chestnut oak bark. Wood Sci. 7:185-190.

Binotto, A. P., W. K. Murphey, and B. E. Cutter. 1971. X-ray diffraction studies of cellulose from bark and wood. Wood and Fiber 3:179-181.

Blankenhorn, P. R., L. E. Rishel, W. K. Murphey, and D. E. Kline. 1977. Some mechanical properties of impregnated bark board. For. Prod. J. 27(6):31-38.

Block, S. S., and S. N. Rao. 1962. Sawdust compost for mushroom growing. Mushroom Sci. 5:134-142.

Boehmer, W. D. and J. C. Rennie. 1976. Predicting diameter inside bark for some hardwoods in west Tennessee. Wood Sci. 8:209-212.

Bollen, W. B., and D. W. Glennie. 1963. Fortified bark for mulching and soil conditioning. For. Prod. J. 13:209-215.

Borger, G. A. and T. T. Kozlowski. 1972. Effects of temperature on first periderm and xylem development in *Fraxinus pennsylvanica*, *Robinia pseudoacacia*, and *Ailanthus altissima*. Can. J. of For. Res. 2:198-205.

Brown, K. J. 1956. Effect of bark in the sulphate pulping of a northern oak mixture. Tappi 39:443-448.

Caldwell, D. H. 1953. Natural variation observed in shagbark hickory, *Carya ovata* (Mill.) K. Koch, in central New York. Rep. North. Nut Growers' Assoc. 44:22-39.

Cappaert, I., O. Verdonck, and M. DeBoodt. 1975. Composting of hardwood bark. Compost Sci. 16(4):12-15.

Carson, H. T., and D. W. Weeter. 1980. Wood ash: Utilization vs. disposal. *In* Organic and fuel uses for bark and wood residues. (R. C. Allison, ed.) Proc. No. P-80-27. For. Prod. Res. Soc., Madison, Wis. p. 40-44.

Cassens, D. L. and E. T. Choong. 1975. Fuel values and volumes for selected delta hardwood barks. South. Lumberman 231 (2862):13-14.

Cassens, D. L. and E. T. Choong. 1976. Fuel values of southern hardwood mill residues. South. Lumberman 233(2893):11-14.

Chafe, S. C., and M. E. Doohan. 1972. Observation of the ultrastructure of the thickened sieve wall in *Pinus strobus* L. Protoplasma 75:67-78.

Chamberlain, E. B. and H. A. Meyer. 1950. Bark volume in cordwood. Tappi 33:554-555.

Chang, Y.-P. 1954. Anatomy of common North American pulpwood barks. Tappi Monogr. Ser. 14, p. 127-146.

Chang, Y.-P., and R. L. Mitchell. 1955. Chemical composition of common North American pulpwood bark. Tappi 38:315-320.

Chao, Y. S. 1976. Hardwood whole-tree chip utilization at one southern kraft mill. FPRS Sep. No. MS-75-S69, 4 p. For. Prod. Res. Soc., Madison, Wis.

Cheadle, V. I., and K. Esau. 1964. Secondary phloem of *Liriodendron tulipifera*. Univ. Calif. Pubs. Bot. 36:143-252.

Choong, E. T. 1974. Heat of combustion of wood and bark of sweetgum. LSU Wood Util. Notes No. 24, 2 p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A & M Coll., Baton Route, La.

Choong, E. T., G. Abdullah, and J. Kowalczuk. 1976. Mineral content in bark and wood of selected delta hardwoods. LSU Wood Util. Notes No. 29, 4 p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A & M Coll., Baton Route, La.

Choong, E. T. and D. L. Cassens. 1976a. Physical characteristics of bark of several delta hardwoods. LSU Wood Util. Notes No. 28, 4 p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A & M Coll., Baton Rouge, La.

Choong, E. T. and D. L. Cassens. 1976b. Fuel values, moisture content, and density of fresh and piled Louisiana hardwood sawmill residues. LSU Wood Util. Notes No. 31, 4 p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A & M Coll., Baton Rouge, La.

Choong, E. T., B.-Y. Chang, and J. Kowalczuk. 1974. Mineral content of wood and bark of sweetgum. LSU Wood Util. Notes No. 27, 4 p. Agric. Exp. Stn. Res., La. State Univ. & A & M Coll., Baton Route, La.

Choong, E. T. and P. J. Fogg. 1976. Extractives content and cell-wall specific gravity in sweetgum. LSU Wood Util. Notes No. 30, 4 p. Agric. Exp. Stn. Res. Rel., La. State Univ. & A & M Coll., Baton Rouge, La.

Chow, P. 1973. The degree of acidity of selected hardwood barks from the midwest. *In* Techniques of processing bark and utilization of bark products. For. Prod. Res. Soc. Proc., p. 64-65. Madison, Wis.: For. Prod. Res. Soc.

Chow, P. 1976. Properties of medium-density, dry-formed fiberboard from seven hardwood residues and bark. For. Prod. J. 26(5): 48-55.

Chow, P. 1979. Phenol adhesive bonded medium-density fiberboard from *Quercus rubra* L. bark and sawdust. Wood and Fiber 11:92-98.

Chow, P. 1980. Hardwood utilization. Illinois Research 22(2):12-13. (Spring 1980.)

Chow, P., C. S. Walters, and J. K. Guiher. 1973. Specific gravity, bulk density, and screen analysis of midwestern plant-fiber residues. For. Prod. J. 23(2):57-60.

Clark III, A. 1976. Sawmill residue yields from yellow-poplar saw logs. For. Prod. J. 26(1):23-27.

Clark, A., III. 1978. Total tree and its utilization in the southern United States. For. Prod. J. 28(10):47-52.

Clark, A. III, D. R. Phillips, and J. G. Schroeder. 1980a. Predicted weights and volumes of northern red oak trees in western North Carolina. Res. Pap. SE-209, U.S. Dep. Agric., For. Serv. 22 p.

Clark, A. III, D. R. Phillips, and H. C. Hitchcock III. 1980b. Predicted weights and volumes of scarlet oak trees on the Tennessee Cumberland Plateau. Res. Pap. SE-214, U.S. Dep. Agric. For. Serv. 23 p.

Clark, A. III, D. R. Phillips, and H. C. Hitchcock III. 1980c. Predicted weights and volumes of southern red oak trees on the Highland Rim in Tennessee. Res. Pap. SE-208, U.S. Dep. Agric., For. Serv. 23 p.

Clark, A. III, and J. G. Schroeder. 1977. Biomass of yellow-poplar in natural stands in western North Carolina. U.S. Dep. Agric. For. Serv. Res. Pap. SE-165. 41 p.

Clark, A. C. III, M. A. Taras, and J. G. Schroeder. 1974. Predicted green lumber and residue yields from the merchantable stem of yellow-poplar. U.S. Dep. Agric. For. Serv., Res. Pap. SE-119. 15 p.

Colannino, A. 1976. Weight equations for white oak and chestnut oak in northern West Virginia. MS Thesis, West Va. University, Morgantown. 75 p.

Core, H. A., W. A. Côté, and A. C. Day. 1979. Wood structure and identification. Syracuse Univ. Press., Syracuse, N.Y. 2nd ed. 182 p.

Daft, G. C., H. A. Poole, and H. A. J. Hoitink. 1979. Composted hardwood bark: A substitute for steam sterilization and fungicide drenches for control of poinsettia crown and root rot. HortSci. 14(2):185-187.

DeCamp, F. B. 1980. The accelerated composting of hardwood bark for use as growing media. *In* Organic and fuel uses for bark and wood residues. (R. C. Allison, ed.) Proc. No. P-80-27, For. Prod. Res. Soc., Madison, Wis. p. 4-5.

deZeeuw, C. H. 1939. Histology of periderm formation in certain northeastern trees, with statistical data on the time of production of deep cork. M.S. Thesis. College of Forestry, New York State Univ., Syracuse. 129 p.

Dunn, S., and J. D. Emery. 1959. Wood waste in composts. For. Prod. J. 9:277-281.

Einspahr, D. W. and M. Harder. 1976. Hardwood bark properties important to the manufacture of fiber products. For. Prod. J. 26(6):28-31.

Einspahr, D. W., and M. L. Harder. 1980. Increasing hardwood fiber supplies through improved bark utilization. Tappi 63(19):121-124.

Einspahr, D. W., M. L. Harder, E. W. Hsu, and P. J. Vizvary. 1979. Kraft pulping characteristics of hickory wood/bark mixtures. TAPPI 62(10):115-118.

Emanuel, D. M. 1971. Power mulchers can apply hardwood bark mulch. U.S. Dep. Agric. For. Serv., Res. Note NE-135, 6 p.

Emanuel, D. M. 1976. Hydromulch: a potential use for hardwood bark residue. U.S. Dep. Agric. For. Serv., Res. Note NE-226. 3 p.

Emanuel, D. M. 1978. Processing hardwood bark residues by screening. U.S. Dep. Agric. For. Serv. Res. Note NE-260. 3 p.

Esau, K. 1965. Plant anatomy. 2nd ed. John Wiley & Sons, Inc., New York. 767 p.

Esau, K. 1969. Encyclopedia of plant anatomy: The phloem. Gebrüder Borntraeger, Berlin. 505 p.

Esau, K. 1977. Anatomy of seed plants. 2nd ed. John Wiley and Sons, New York. 550 p.

Esau, K., and V. I. Cheadle. 1958. Wall thickening in sieve elements. *In* Proc., Natl. Acad. Sci. U.S. 44:546-553.

Evert, R. F. 1963. Ontogeny and structure of the secondary phloem in *Pyrus malus*. Amer. J. Bot. 50:8-37.

Evert, R. F., C. M. Tucker, J. D. Davis, and B. P. Deshpande. 1969. Light microscope investigation of sieve element ontogeny and structure in *Ulmus americana*. Amer. J. Bot. 56:999-1017.

Ezell, A. W., and J. L. Stewart. 1978. The length of phloem fibres in sweetgum (*Liquidambar styraciflua* L.). Wood and Fiber 10(3):186-187.

Feustel, I. C., and H. C. Byers. 1930. The physical and chemical characteristics of certain American peat profiles. U.S. Dep. Agric. Tech. Bull. 214, 27 p.

Fisher, J. L., Jr. 1974. Methods for packaging wood waste—the Hobbs open mouth bagging systems. FPRS Sep. No. AM-74-S5, 3 p. For. Prod. Lab., Madison, Wis.

Frey, A. 1925. Calciumoxalat-Monohydrat and -Trihydrat in der Pflanze. Vierteljahrsschrift Naturforschenden Gesellschaft in Zurich 70:1-65.

Frey-Wyssling, A., and F. Blank. 1938. Über knieformige oxalatkristalle von *Caryocar nuciferum* L. Protoplasma 31:194-198.

Galezewski, J. A. 1977. Method of making cellular materials from red oak bark. For. Prod. J. 27(12):21-24.

Gartner, J. B., M. M. Meyer, Jr., and D. C. Saupe. 1971. Hardwood bark as a growing media for container-grown ornamentals. For. Prod. J. 21(5):25-29.

Gartner, J. B., and D. J. Williams. 1978. Horticultural uses for (hardwood) bark—A review of current research. Tappi 61(7): 83-86.

Graves, D. H., and S. B. Carpenter. 1980. Use of hardwood bark in stripmine reclamation. *In* Organic and fuel uses for bark and wood residues. (R. C. Allison, ed.) Proc. No. P-80-27, For. Prod. Res. Soc., Madison, Wis. p. 6-12.

Gray, R. L. 1974. Anatomy of the secondary xylem of *Vitex* (family Verbenaceae). Ph.D. Dissertation, SUNY College of Environ. Sci. and For., Syracuse, N.Y. 255 p.

Gray, R. L., and W. A. Côté. 1974. SEM/EDXA as a diagnostic tool for wood and its inclusions. IAWA Bull. 3:6-11. Internat. Assoc. Wood Anatomists.

Griffin, G. 1979. Bark: Processing or burning: Either way, it means dollars. Timber Proc. Ind. 4(3):29-33.

Grosenbaugh, L. R. 1967. STX—Fortran-4 program for estimates of tree populations from 3P sample-tree-measurements. U.S. Dep. Agric., For. Serv., Res. Pap. PSW-13. 76 p.

Guttenberg, S. 1951. Listen to the bark. South. Lumberman 183(2297):220-222.

Hailwood, A. J. and S. Horrobin. 1946. Absorption of water by polymers: analysis in terms of a simple model. Trans. Faraday Soc. 42B:84-102.

Hall, C. S. 1974. Bonding raw and composted bark with starch adhesives. FPRS Sep. No. CC-73-10, 9 p. For. Prod. Res. Soc., Madison, Wis.

Harder, M. L. and D. W. Einspahr. 1976. Bark fuel value of important pulpwood species. Tappi 59(12):132.

Harder, M. L., and D. W. Einspahr. 1978. An update of bark fuel values of important pulpwood species. Tappi 61(12):87-88.

Harder, M. L., D. W. Einspahr, and R. A. Parham. 1978. Bark fibrous yield for 42 pulpwood species. Tappi 61(11):121-122.

Harkin, J. M. and J. W. Rowe. 1971. Bark and its possible uses. U.S. Dep. Agric. For. Serv., Res. Note FPL-091. 56 p.

Harlow, W. M., E. S. Harrar, and F. M. White. 1979. Textbook of dendrology. 6th ed. New York: McGraw-Hill Book Company. 510 p.

Haynes, D. L. 1968. U.S. Plywood-Champion Paper, Inc. program of processing and marketing southern barks. *In* Making and selling bark products. (Mater, J., R. Martin, D. Williams, R. Sarles, F. Lamb, and R. Allison, eds.) Madison, Wis: For. Prod. Res. Soc. p. 78-81.

Hemingway, R. W. 1981. Bark: Its chemistry and prospects for chemical utilization. *In* Organic chemicals from biomass. p. 189-248. (I. S. Goldstein, ed.) CRC Press, Inc., Boca Raton, Fla.

Hemingway, R. W. In press. Plant phenolic compounds. *In* Handbook of biosolar resources. Vol. IV, Resource Products/Applications. C. R. Keim, F. Shafizadeh, ed. CRC Press.

Hergert, H. L., L. E. Van Blaricom, J. C. Steinberg, and K. R. Gray. 1965. Isolation and properties of dispersants from western hemlock bark. For. Prod. J. 15:485-491.

Hirata, T., H. Saiki, and H. Harada. 1973. Observation of crystals and silica inclusions in parenchyma cells of certain tropical woods by scanning electron microscope. Bull. Kyoto Univ. For. 44:194-205.

Hoitink, H. A. J., A. F. Schmitthenner, and L. J. Herr. 1975. Composted bark for control of root rot in ornamentals. Ohio Rep. 60(2):25-26.

Holdheide, W. 1951. Anatomie mitteleuropäischer Gehölzrinden. *In* H. Freund's Handbuch der Mikroscopie in der Technik. Vol. 5, Part I, p. 193-367. Umschau Verlag: Frankfurt-am-Main.

Holmes, R. L., G. D. Coorts, and P. L. Roth. 1973. Hardwood bark chips as a surfacing material for recreation trails. For. Prod. J. 23(5):25-30.

Host, J. R., and R. Pfenninger. 1978. Plant nutrients in flyash from bark-fired boilers. Res. Note INT-247, U.S. Dep. Agric. For. Serv. 7 p.

Hough, W. A. 1969. Caloric value of some forest fuels of the southern United States. U.S. Dep. Agric. For. Serv., Res. Note SE-120. 6 p.

Howard, E. T. 1971. Bark structure of the southern pines. Wood Sci. 3:134-148.

Howard, E. T. 1977. Bark structure of southern upland oaks. Wood and Fiber 9:172-183.

Huber, B. 1958. Anatomical and physiological investigations on food translocation in trees. Pages 367-379 *in* K. V. Thimann, ed., The physiology of forest trees. Ronald Press, New York.

Joiner, J. N., and C. A. Conover. 1969. Southern pine bark market in horticulture analyzed. For. Ind. 96(5):37.

Kajita, H. 1975. The bark-water relationship. J. of the Soc. of Mater. Sci. Jap. 24(264):862-866.

Keller, E. L. 1950. Effect of bark in the neutral sulphite semichemical pulping of aspen, hickory, and slash pine. Tappi 33(11):556-560.

Kellison, R. C. 1967. A geographic variation study of yellow-poplar (*Liriodendron tulipifera* L.) within North Carolina. Tech. Rep. No. 33, 41 p. N.C. State Univ., Raleigh, N.C.

Knutson, R. G. 1975. The highway market for mulch—an opportunity for bark producers. The North. Logger and Timber Proc. 23(12):13, 32-33.

Koch, C. B. 1970. Variation in bark specific gravity of selected Appalachian hardwoods. Wood Sci. 3:43-47.

Koch, C. B. 1971a. Thickness and specific gravity of inner and outer bark of red oak and yellow-poplar. Wood Sci. 3:214-217.

Koch, C. B. 1971b. Bark volume of yellow-poplar, red, black, and scarlet oak, and red maple in Northern West Virginia. West Va. Univ. Agric. Exp. Stn. Bull. 602T, 20 p.

Koch, P. 1972. Utilization of the southern pines. U.S. Dep. Agric. For. Serv., Agric. Handb. 420. 1663 p. 2 vol. U.S. Govt. Print. Off., Washington, D.C.

Koch, C. B., and C. S. Hall. 1978. Utilization of hardwood bark for production of semi-durable bark-board. West Virginia For. Notes 2:5-8.

Koljo, B. 1950. (Notes on thermal phenomena in timber and trees.) Forstwiss. Centralbl. 69:538-551.

Krause, H. H. 1962. Assembly for the preparation of sawdust and peat composts. J. For. 60:563-565.

Labosky, P., Jr., J. W. Dick, K. A. Holleman, and D. T. So. 1977a. Utilization of bark residues as poultry litter. For. Prod. J. 27(1):28-32.

Labosky, P., Jr., J. W. Dick, and D. L. Cross. 1977b. Bark broiler litter as a potential feedstuff for ruminants. Poultry Sci. 56:2064-2069.

Leonard, R. E., and S. C. Fay. 1978. A compost bin for handling privy wastes: Its fabrication and use. U.S. Dep. Agric. For. Serv. Res. Note NE-254. 6 p.

Lightsey, G. R. and J. W. Mitchell. 1975. Pine bark effectively used as trickling filter medium. Can. Pulp & Pap. 29(11):27-28, 30.

Lightsey, G. R., J. W. Mitchell, and J. Travis. 1976. Bark as trickling-filter dewatering medium for primary sludge. For. Prod. J. 26(12):17-21.

Lunt, H. A. 1955. The use of woodchips and other wood fragments as soil amendments. Bull. 593, The Conn. Agric. Exp. Stn., New Haven, Conn. 46 p.

Lunt, O. R., and B. Clark. 1959. Horticultural applications for bark and wood fragments. For. Prod. J. 9(4):39A-42A.

McCool, M. M. 1949. Studies on pH values of sawdusts and soil-sawdust mixtures. Boyce Thompson Inst. Contr. 15(5):279-282.

MacDaniels, L. H. 1918. The histology of the phloem in certain woody angiosperms. Amer. J. Bot. 5:347-378.

McGovern, J. N., C. E. Zehner, and J. B. Boyle. 1977. Investigation of bark residues for livestock bedding. For. Prod. J. 27(7):29-34.

McGrath, J. J. 1966. Secondary phloem in ash (*Fraxinus velutina*): Anatomy and seasonal changes. Ph.D. Dissertation. Univ. Calif., Davis. 212 p.

McMillin, C. W., and F. G. Manwiller. 1980. The wood and bark of hardwoods growing on southern pine sites—A pictorial atlas. Gen. Tech. Rep. SO-29, U.S. Dep. Agric., For. Serv. 58 p.

Mahmood, A. 1965. Secondary walls in phloem of *Pinus radiata* D. Don. Nature 207:656-658.

Maisenhelder, L. C. 1970. Magnolia (*Magnolia grandiflora* and *Magnolia virginiana*). Am. Woods Leafl. FS-245. 8 p. U.S. Dep. Agric. For. Serv., Washington, D.C.

Malek, R. B. and J. B. Gartner. 1975. Hardwood bark as a soil amendment for suppression of plant parasitic nematodes on container-grown plants. Hortsci. 10(1):33-35.

Manwiller, F. G. 1975. Wood and bark moisture content of small-diameter hardwoods growing on southern pine sites. Wood Sci. 8:384-388.

Manwiller, F. G. 1979. Wood and bark specific gravity of small-diameter pine-site hardwoods in the South. Wood Sci. 11:234-240.

Martin, R. E. 1963. Thermal and other properties of bark and their relation to fire injury of tree stems. PhD thesis, Univ. Mich., Ann Arbor. 256 p.

Martin, R. E. 1967. Interim equilibrium moisture content values of bark. For. Prod. J. 17(4):30-31.

Martin, R. E. 1968. Interim volumetric expansion values for bark. For. Prod. J. 18(4):52.

Martin, R. E. 1970. Directional thermal conductivity ratios of bark. Holzforschung 24:26-30.

Martin, R. E. and J. B. Crist. 1968. Selected physical-mechanical properties of eastern tree barks. For. Prod. J. 18(11):54-60.

Martin, R. E., and J. B. Crist. 1970. Elements of bark structure and terminology. Wood and Fiber 2:269-279.

Massengale, R. 1971. Sawdust, slab and edging weights from mixed oak logs from the Missouri Ozarks. The North. Logger and Timber Proc. 19(10):28-29.

Mater, J., Ed. 1972. Techniques of processing bark and utilization of bark products. 65 p. Madison, Wis.: For. Prod. Res. Soc.

Mater, J. (ed.) 1974. Technological options in bark utilization. Proc. No. P-73/74-11. For. Prod. Res. Soc., Madison, Wis. 176 p.

Mater, J. 1977a. Potential of the utilization of poultry manure as a source of nitrogen in composting bark. For. Prod. J. 27(1):37-40.

Mater, J. (ed.) 1977b. Utilizing bark and wood residues to solve technical problems. FPRS Proc. No. P-77-20, 104 p. For. Prod. Res. Soc., Madison, Wis.

Mater, J., R. Martin, D. Williams, R. Sarles, F. Lamb, and R. Allison, Ed. 1968. Making and selling bark products. 88 p. Madison, Wis.: For. Prod. Res. Soc.

Mesavage, C. 1969. Measuring bark thickness. J. For. 67:753-754.

Mia, A. J. 1969. Study of cell wall in angiospermous plants using light and electron microscope. Wood Sci. 2:1-10.

Miller, R. W., and W. G. Van Beckum. 1960. Bark and fiber products for oil well drilling. For. Prod. J. 10:193-195.

Millikin, D. C. 1955. Determination of bark volumes and fuel properties. Pulp and Pap. Mag. of Can. 56(13):106-108.

Mitchell, R. L. 1958. Chemistry of hickory. U.S. Dep. Agric. For. Serv., Hickory Task Force Rep. No. 2. 12 p. Southeast. For. Exp. Stn., Asheville, N.C.

Moore, W. E., and D. B. Johnson. 1967. Procedures for chemical analysis of wood and wood products. U.S. Dept. Agric., For. Serv., For. Prod. Lab., Madison, Wis.

Morris, W. C. and D. C. Milbocker. 1972. Repressed growth and leaf chlorosis of Japanese holly grown in hardwood bark. Hortscience 7(5):486-487.

Murphey, W. K., F. C. Beall, B. E. Cutter, and R. C. Baldwin. 1970. Selected chemical and physical properties of several bark species. For. Prod. J. 20(2):58-59.

Murphey, W. K. and B. E. Cutter. 1974. Gross heat of combustion of five hardwood species at differing moisture contents. For. Prod. J. 24(2):44-45.

Murphey, W. K., and L. E. Rishel. 1969. Relative strength of boards made from bark of several species. For. Prod. J. 19(1):52.

Nanko, H. 1978. Cell wall structure of the sclereids in the secondary phloem of *Populus euramericana*. Mokuzai Gakkaishi 24:362-368.

Nanko, H. 1979. Studies on the development and cell wall structure of sclerenchymatous elements in the secondary phloem of woody dicotyledons and conifers. PhD Dissertation. Dept. of Wood Sci. and Technol., Kyoto University, Japan.

Nanko, H., and W. A. Côté, Jr. 1980. Bark structure of hardwoods grown on southern pine sites. Renewable Materials Institute Series No. 2, Syracuse University Press, Syracuse, N.Y. 56 p.

Nanko, H., H. Saiki, and H. Harada. 1976. Cell wall development of chambered crystalliferous cells in the secondary phloem of *Populus curamericana*. Bull. Kyoto Univ. For. 48:167-177.

Nanko, H., H. Saiki, and H. Harada. 1977. Development and structure of the phloem fibers in the secondary phloem of *Populus euramericana*. J. Jap. Wood Res. Soc. 23:267-272.

National Council of the Paper Industry for Air and Stream Improvement, Inc. 1978. Information on the sulfur content of bark and its contribution to SO_2 emissions when burned as a fuel. Atmospheric Quality Improve. Bull. No. 96. NCASI, New York. 12 p.

Nyland, R. D. 1971. Average bark thickness at top of butt log for several New York hardwoods. AFRI Res. Note No. 3, 1 p. Appl. For. Res. Inst., State Univ. Coll. of For., Syracuse, N.Y.

Okoh, I. K. A. 1976. Moisture sorption and electrical resistivity of some woods and barks. Ph.D. thesis. State Univ. of N.Y. Coll. of Environ. Sci. and For., Syracuse, N.Y. 183 p.

Okoh, K. I., and C. Skaar. 1980. Moisture sorption isotherms of the wood and inner bark of ten southern U.S. hardwoods. Wood and Fiber 12:98-111.

Page, R. H. and H. O. Baxter. 1974. A new look at residues from Georgia's primary wood manufacturing industries. Ga. For. Res. Pap. 78, 11 p. Macon, Ga.: Ga. For. Res. Counc.

Parameswaran, N. 1975. (On the fine structure of the wall of sclereids in some tree barks.) Protoplasma 85:305-314.

Parameswaran, N., and W. Liese. 1970. Mikroskopie der Rinde tropischer Holzarten. *In*: H. Freund, Handbuch der Mikroskopie in der Technik, Frankfurt am Main, Umschau Verlag.

Phillips, D. R. 1975. Lumber and residue yields for black oak saw logs in western North Carolina. For. Prod. J. 25(1):29-33.

Phillips, D. R. 1981. Predicted total-tree biomass of understory hardwoods. Res. Pap. SE-223. U.S. Dep. Agric., For. Serv. 22 p.

Phillips, D. R. and J. G. Schroeder. 1973. Some physical properties of yellow-poplar wood and bark. Part I—seasonal moisture content. Wood Sci. 5:265-269.

Phillips, D. R., J. G. Schroeder, and M. A. Taras. 1974. Predicted green lumber and residue yields from the merchantable stem of black oak trees. USDA For. Serv. Res. Pap. SE-120, 10 p. Southeast. For. Exp. Stn., Asheville, N.C.

Plaisance, G., and A. Cailleux. 1958. (Dictionary of soils). La Maison Rastique Publishers, Paris.

Porterfield, R. L. and W. W. von Segen. 1975. Utilization efficiency during harvesting and primary manufacturing in Arkansas. Final Rep. of Gen. For. Assist. Proj. Wood Util. Surv.-Ark. For. Comm., 42 p.

Postek, M. T., K. S. Howard, A. H. Johnson, and K. L. McMichael. 1980. Scanning electron microscopy: A student's handbook. Ladd Research Industries, Inc. 305 p.

Powell, L. N., J. D. Shoemaker, R. Lazer, and R. G. Barker. 1975. Whole-tree chips as a source of papermaking fiber. Tappi 58(7):150-155.

Randall, J. M. 1977. Variations in effectiveness of barks as scavengers for heavy metal ions. For. Prod. J. 27(11):51-56.

Randall, J. M., R. L. Bermann, V. Garrett, and A. C. Waiss, Jr. 1974. Use of bark to remove heavy metal ions from waste solutions. For. Prod. J. 24(9):80-84.

Reethof, G., L. D. Frank, and O. H. McDaniel. 1976. Absorption of sound by tree bark. U.S. Dep. Agric. For. Serv., Res. Pap. NE-341, 6 p.

Rishel, L. E., P. R. Blankenhorn, and W. K. Murphey. 1980. A note on the flexural properties of bark board. Wood and fiber 11:233-236.

Rowe, J. W., and A. H. Conner. 1979. Extractives in eastern hardwoods—A review. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. FPL 18. 66 p.

Russell, E. W. 1961. Soil conditions and plant growth. 688 p. London: Longmans, Green and Co., Ltd.

Salomon, M. 1953. The accumulation of soil organic matter from wood chips. Proc. Soil Sci. Soc. Amer. 17(2):114-118.

Sandala, M. G., P. R. Blankenhorn, and D. E. Kline. 1981. Thermal analysis of white oak, northern red oak, and black cherry bark chemical components. Wood Sci. 13:157-165.

Sarles, R. L. 1975. New equipment for bark application, pp. 7-24. *In* Technological options in bark utilization. Madison, Wis.: For. Prod. Res. Soc.

Sarles, R. L., and D. M. Emanuel. 1977a. Hardwood bark mulch for revegetation and erosion control on drastically disturbed sites. J. Soil and Water Conservation 32:209-214.

Sarles, R. L. and D. M. Emanuel. 1977b. The mobile bark blower: an evaluation of performance and costs. U.S. Dep. Agric. For. Serv., Res. Pap. NE-368. 9 p.

Schnell, R. L. 1978. Biomass estimates of hickory tree components. Tech. Note B30, Div. For. Fish., and Wildl. Dev., Tenn. Val. Auth., Norris, Tenn. 39 p.

Schnur, G. L. 1937. Yield, stand, and volume tables for even-aged upland oak forests. U.S. Dep. Agric. For. Serv., Tech. Bull. No. 560. 87 p.

Schroeder, J. G. and D. R. Phillips. 1973. Some physical properties of yellow-poplar wood and bark. Part II: variations with height in the tree. Wood Sci. 6:123-126.

Scott, E. G. and B. C. Bearce. 1972. A hardwood-bark-sawdust compost for greenhouse pot flower production. For. Prod. J. 22(1):36-39.

Scurfield, G., A. J. Mitchell, and S. R. Silva. 1973. Crystals in woody stems. Bot. J. Linn. Soc. 66:277-289.

Sitte, Von P. 1957. Der Einbau der Kork-Zellwande. *In* E. Treiber, ed., Die Chemie der Pflanzenzellwand. Springer-Verlag, Berlin. 511 p.

Smith, R. S., and T. S. Coulter. 1980. Use of lightweight sawmill residues in highway embankments. RTAC Forum 3(1):84-89.

Smith, E. M., and S. A. Treaster. 1981. Evaluating hardwood and pinebark media for container grown woody ornamentals. Res. Circ. No. 263:3-6. Ohio Res. and Develop. Cent.

Somers, T. C., and A. F. Harrison. 1967. Wood tannins—isolation and significance in host resistance to *Verticillium* wilt disease. Aust. J. Biol. Sci. 20:475-479.

Space, J. C. 1973. 3-P forest inventory—design, procedures, data processing. U.S. Dep. Agric., For. Serv. State and Private Forestry, Southeastern Area, Atlanta, Ga.

Spomer, L. A. 1973. Soils in plant containers: soil amendment, air and water relationships. Ill. Res. 15(3):16-17.

Spomer, L. A. 1974. Optimizing container soil amendment: The "threshold proportion" and prediction of porosity. Hortsci. 9(6):532-533.

Spomer, L. A. 1975a. Availability of water absorbed by hardwood bark soil amendment. Agron. J. 67:589-590.

Spomer, L. A. 1975b. How much hardwood bark is necessary for proper container-soil amendment. For. Prod. J. 25(2):57-59.

Spomer, L. A. 1975c. Small soil containers as experimental tools: soil water relations. Commun. Soil Sci. and Plant Anal. 6(1):21-26.

Srivastava, L. M. 1964. Anatomy, chemistry, and physiology of bark. *In* J. A. Romberger and P. Mikola, eds. International review of forestry research, Vol. 1. Academic Press, New York. 240 pp.

Still, S. M., M. A. Dirr, and J. B. Gartner. 1975. Growth of Bright Golden Anne Chrysanthemums in hardwood bark amended media as affected by nitrogen level and state of decomposition. For. Prod. J. 25(1):54-57.

Still, S., J. B. Gartner, and T. D. Hughes. 1972. Effect of sawdust age and nitrogen application on chrysanthemums grown in white oak sawdust media. For. Prod. J. 22(9):111-114.

Szopa, P. S., D. E. Hartley, and E. A. McGinnes, Jr. 1973. Hardwood bark-amended soil as a potting medium for container-grown chrysanthemums. For. Prod. J. 23(1):43-46.

Tennessee Valley Authority. 1972. Biomass estimates of black oak tree components. Tech. Note B1, 24 p. Norris, Tenn: Tenn. Vall. Auth.

Thode, E. F., J. R. Peckham, and E. J. Daleski. 1961. An evaluation of certain laboratory pulping methods. Tappi 44(2):81-88.

Van Nierop, E. T., and D. P. White. 1958. Evaluation of several organic mulching materials on a sandy loam forest nursery soil. J. For. 56(1):23-27.

Wardrop, A. B. 1976. Lignification of the plant cell wall. J. Appl. Polym. Sci., Appl. Polym. Symp. 28:1041-1063.

Wartluft, J. L. 1972. Weight of bark residues from hardwood logs. *In* Techniques of processing bark and utilization of bark products. (J. Mater, Ed.) For. Prod. Res. Soc., Madison, Wis., p. 56-63.

Wartluft, J. L. 1974a. Yield table for hardwood bark residue. U.S. Dep. Agric. For. Serv. Res. Note NE-199. 4 p.

Wartluft, J. L. 1974b. Baling hardwood bark with a vertical baler. North. Logger and Timber Proc. 22(12):22.

Wartluft, J. L. 1977. Weights of small Appalachian hardwood trees and components. U.S. Dep. Agric. For. Serv., Res. Pap. NE-366. 4 p.

Wartluft, J. L. 1978. Estimating top weights of hardwood sawtimber. U.S. Dep. Agric. For. Serv. Res. Pap. NE-427. 7 p.

Welch, R. L. and T. R. Bellamy. 1976. Wood utilization within the primary wood-using industry. For. Prod. J. 26(6):13-16.

Weldon, D. 1970. Scavenging oil with southern pine bark. Tex. For. Serv., Prod. Lab. Publ. 106. 3 p. Lufkin.

Whittaker, R. H., N. Cohen, and J. S. Olson. 1963. Net production relations of three tree species at Oak Ridge, Tennessee. Ecol. 44:806-810.

Wiant, H. V., Jr., and F. Castaneda. 1978. Preliminary weight yield tables for evenaged upland oak forests. Bull. 664T. West Virginia Univ., Agric. and For. Exp. Stn., Morgantown. 20 p.

Wiant, H. V., Jr. and C. B. Koch. 1974. Predicting diameters inside bark from outside bark measurements on some Appalachian hardwoods. J. of For. 72:775.

Wiant, H. V., Jr., C. E. Sheetz, A. Colaninno, J. C. DeMoss, and F. Casteneda. 1977. Tables and procedures for estimating weights of some Appalachian hardwoods. Bull. 659T, West. Va. Univ. Agric. and For. Exp. Stn., Morgantown. 36 p.

Wiant, H. V., Jr., and D. E. Wingerd. 1981. Biomass factors for point sampling in Appalachian hardwoods. J. For. 79 (1):21, 29.

Wilde, S. A. 1958. Marketable sawdust composts: their preparation and fertilizing value. For. Prod. J. 8(11):323-326.

Wiley, A. 1976. Combustion fundamentals. *In* Energy production from residues. Proc. of the 9th Texas Ind. Wood Sem., p. 9-15. Lufkin, Tex.: Tex. For. Prod. Lab.

Woldseth, R. 1973. All you ever wanted to know about X-ray energy spectrometry. Burlingame, CA: Kevex Corporation.

World Wood. 1977. Bark can make foam products. World Wood 18(3):29.

Young, H. E. 1971. Preliminary estimates of bark percentages and chemical elements in complete trees of eight species in Main. For. Prod. J. 21(5):56-59.

Zahur, M. S. 1959. Comparative study of secondary phloem of 423 species of woody dicotyledons belonging to 85 families. Cornell Agric. Exp. Stn. Memoir 358. Ithaca, N.Y. 160 p.

14

Roots

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CHAPTER 14

Roots

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CHAPTER 14

Roots

14-1 PHYSIOLOGY

The physiology and growth of hardwood roots have received considerable study by specialists in forest regeneration and culture. Since their findings have little direct bearing on possible use for roots, they are not abstracted in this text. Readers needing a bibliography of the physiology and rooting habits of commercial tree species of the Eastern United States should consult Smith and Every (1980); the 1,360 entries in this reference are organized by species—including the 22 pine-site hardwoods under study here—and by subject (root growth and development, root functions, root biological interactions, and root responses to nursery and forestry practices).

One aspect of hardwood physiology is particularly significant in the competition between understory hardwoods and southern pines—the pines are tolerant of ground fires, whereas the hardwoods are not. Grano (1970) found that in an Arkansas loblolly-shortleaf pine stand containing abundant litter, one winter fire killed 94 percent of the stems of understory hardwoods up to 3.5 inches in diameter at the base. Prolific sprouting ensued. Eleven annual summer burns eliminated sprouting in 85 percent of the rootstocks, and seven biennial summer burns eliminated sprouting on 59 percent of them.

Flooding is a not infrequent occurrence on some sites where both hardwoods and pines compete. In general, the hardwoods endure flooding better than the southern pines; some hardwoods, however, cannot tolerate flooding—e.g., yellow-poplar (Hook and Brown 1973).

14-2 ROOT FORM

Root form varies not only among species, but also within species. Factors affecting the within-species variation include soil type and moisture content, depth to water table, competition, depth of litter, exposure to prevailing winds, tree age, and—in plantations—method of planting.

ESTIMATION OF DBH FROM STUMP DIAMETER

One aspect of stump-root form is the taper in lower stems between the top of a 6-inch-high stump and breast height. Mensurationists observing stumps frequently need to estimate dbh of the tree that stood on the stump. Data facilitating such estimation are summarized in tables 27-138 through 27-140. For relationship of tree dbh to diameter at groundline see figure 16-36. Stump volume, related to diameter and height, are shown in table 27-137.

ROOT FORM RELATED TO PLANTING METHOD

Early development of hardwood seedlings is influenced by method of planting. Seedlings planted in slits do not have the symmetrical root systems typical of seedlings carefully planted in round holes. Loosening of soil in holes dug for planting improves soil structure and soil-air relationships, accelerating early growth of roots and increasing their penetration (Hollis 1966).

ROOT FORMS IN SEEDLINGS

Seedling roots (fig. 14-1) have little potential for utilization but their vigorous development is crucial to successful establishment of hardwood stands. Smith and Every's (1980) bibliography of rooting habits provides a good guide to the literature on seedling root form. See also Lyford (1980) for a description of root development in northern red oak.

ROOT DISTRIBUTION IN FORESTS

Stout (1968) hydraulically excavated the root systems of oaks, maples, ashes, hickories, and other eastern hardwoods. He determined that the area occupied by a tree's roots exceeded its crown area (projected to ground plane) by 3.5:1 to 40.7:1, but that usually the diameter of a root system is a little more than twice the diameter of the crown. Root systems (fig. 14-2) have three rather distinct parts: (1) the root crowns, a roughly globular portion at the base of the tree; (2) the rapid-taper section, comprising the roots which provide lateral support and anchorage; and (3) the network beyond the rapid taper where roots meander and intermingle; roots as small as 1/2-inch in diameter may extend 10 to 20 feet laterally without noticeable change in size. Stout found that invariably, when a lateral root was followed to its end, the end was at the surface. At the normal below-ground level of lateral roots he found forks; one root branch from such a fork grows up to the surface while the other continues parallel. Stout observed this in all species.

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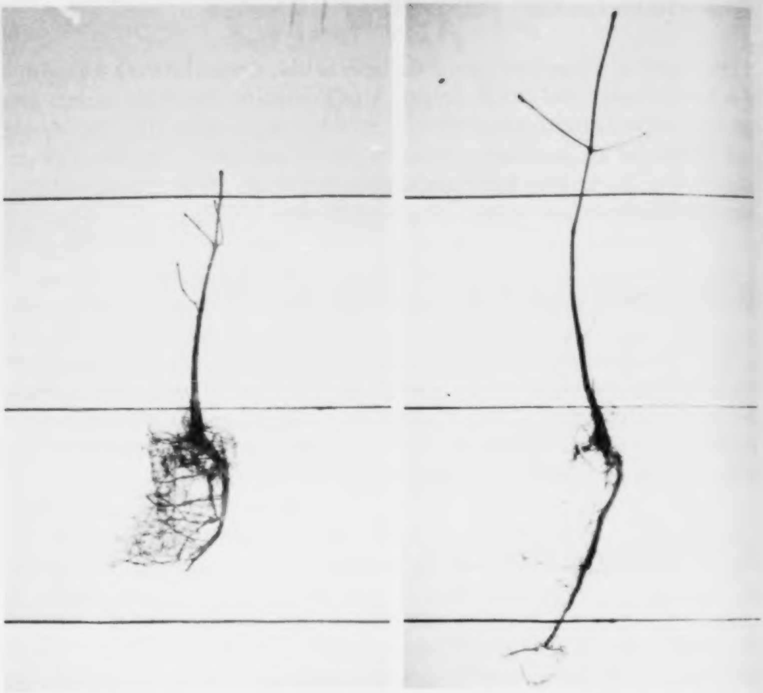

Figure 14-1.—Two northern red oak seedlings grown 4 years from seed in undisturbed forest soil inside of 18-inch lengths of 7-inch-diameter sheet metal pipe open at both ends. Horizontal lines are 12 inches apart. (Photos from files of Ivan Sander, North Cent. For. Exp. Stn., U.S. Dep. Agric., For. Serv., Columbus, Mo.)

Although some hardwood species typically have strong tap roots and all have sinker roots (fig. 14-3) as well as laterals, the greatest volume of roots is usually concentrated in the first foot or two of soil (Kochenderfer 1973).

Roots are not uniformly distributed around trees. In some cases most are downhill from the stump, but in others most are uphill, or to either side. Root grafts between roots of the same species are common—usually where root systems are crowded and within 3 or 4 feet of the stumps. Depth of root penetration varies significantly among and within species. (See next subsection and figures 14-3 through 14-26.)

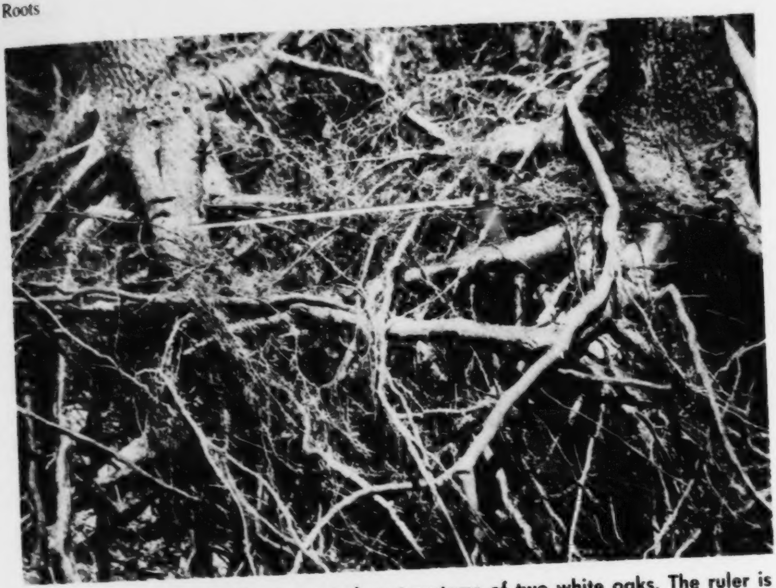

Figure 14-2.—Hydraulically excavated root systems of two white oaks. The ruler is extended 2 feet. The root passing to the left of the stump at right is from another tree approximately 40 feet distant.

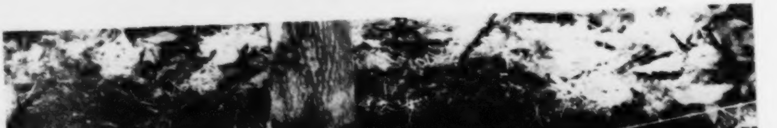

Figure 14-3.—Excavated typical yellow-poplar root system. (Photo from Francis 1979.)

GENERAL COMMENTS ON ROOT FORM

Root forms are extremely variable; the brief descriptions in the following paragraphs are included as a sampling of descriptions applicable to trees of several species and in a variety of sizes.

Ash, green.—Of species studied in a snow-trap planting in North Dakota, green ash had the fourth most extensive root system. The roots of trees 38 feet tall penetrated 48 feet laterally and 3.6 feet downward. The roots were about evenly distributed in the top 3 feet of soil (Wright 1959).

Elm, American.—The root system of American elm is quite plastic, the depth of rooting varying with soil texture and moisture. In heavy wet soils the root system is widespread, with most of the roots within 3 or 4 feet of the surface. On drier medium-textured soils the roots usually penetrate 5 to 10 feet. In deep, relatively dry sands in the Dakotas, American elm may develop a traproot reaching down 18 to 20 feet to the water table (Guilkey 1957).

Hickory, sp.—Revised USDA Handbook No. 271, "Silvics of Forest Trees of the United States," notes that true hickories develop a long taproot with few laterals. The species are windfirm on most soils. Early root growth is primarily in the taproot which typically reaches a depth of 12 to 36 inches during the first year. In mockernut hickory (probably typical of all true hickories), small laterals originate throughout the length of the taproot but many die back during the fall. During the second year, the taproot may reach a depth of 48 inches, and the laterals grow rapidly. After 5 years or so, the root system has attained its maximum depth and the horizontal spread of the roots is about double that of the crown. By age 10, the height of the top is four times the depth of the taproot while the spread of the crown branches is only about half that of the root system.

Maple, red.—Lyford (1980) found that in contrast to the long strong taproots of northern red oak which descend deeply into the ground, red maple taproots are weak, turn aside easily, and become horizontal roots. He noted that red maple woody lateral roots tend to be close to the surface of the mineral soil, emerge from two positions on the taproot so they have a fanlike appearance, and have endotrophic, smooth, bead-like, readily visible root tips in the forest floor; root tips seldom measure less than 0.5 mm in diameter.

Oak, northern red.—Lyford (1980) abstracted his several-year study of northern red oak root systems by noting that they are dominated by 5 to 10 woody major laterals that arise near the soil line from several positions around a long strong taproot that descends vertically deep into the soil. The major laterals extend horizontally through the **B horizon** for distances up to 56 feet; the B horizon is the layer of the soil profile upon which humus rests and in which most root growth occurs. Injury is almost immediately followed by development of replacement roots. This leads to forking and to the coarsely branched woody root system of the forest-grown tree. Laterals on uninjured roots emerge acropetally about every 1 to 2 mm; many laterals grow upwards, into the **A_1** and forest floor horizons (the A_1 horizon is the upper, dark layer of soil composed of a relatively high content of organic matter, but mixed with mineral soil). These laterals elaborate into an enormous number of root tips 0.1 to 0.2 mm in diameter; most are **ectomycorrhizal**, i.e., a symbiotic relationship exists between fungi and living root cells which promotes water and nutrient absorption by the tree.

Oak, white.—R. Rogers of the North Central Forest Experiment Station, Columbia, Missouri, provided (July 15, 1981) the following summary of the rooting habits of white oak (from revised USDA Handbook No. 271, Silvics of Forest Trees of the United States):

> "White oak is deep-rooted—a trait that persists from youth to maturity. White oak seedlings produce a conspicuous well-developed taproot but this gradually disappears with age and is replaced by a fibrous root system with well-developed tapered laterals. Although the deepest point of root penetration observed during a study conducted at the Harvard Black Rock Forest in Massachusetts approached 4 feet, most of the main branches away from the central stem were within 21 inches of the ground surface. Fine roots are typically concentrated in dense mats in the upper soil horizons usually close to trunks but occasionally lying beneath the base of neighboring trees.
>
> Root grafts between neighboring trees are common, especially under crowded conditions. The ratio between the area of the root system and the area of the crown ranges from 3.4:1 to 5.8:1. Following stand thinning, roots of released trees are capable of elongating at the rate of 0.8 foot/year.
>
> Root regeneration of young, forest-grown seedlings may be hampered following top damage. A study of root regeneration of 1-0 white oak seedlings growing under greenhouse conditions has shown that new growth of seedlings whose shoot tops were pruned was 20 to 80 percent less than that of unpruned seedlings."

Sweetgum.—Chittendon and Hatt (1905) noted that root systems of sweetgum differ considerably in various localities. On hardwood bottomland sweetgum commonly has a fairly well-developed taproot and strong branching lateral roots. On ridges and where southern pines grow the root system is deeper, with a very large and long taproot and long superficial roots. In sloughs and swamps the taproot is absent and the root system is flat, very spreading, and has small branched laterals.

Many sweetgum trees arise from root suckers. Such individuals have no taproot, although a lateral may develop into a taproot-like structure. Root connections may be maintained throughout the life of such trees and may become quite thick (J. K. Francis, Southern Forest Experiment Station, Stoneville, MS, correspondence of July 9, 1981).

Yellow-poplar.—Francis (1979) studied rooting habits of pole-size yellow-poplar in Tennessee and found that root configuration is quite variable; a branched taproot with several widely spreading laterals is typical, however (figure 14-3). Rooting depth is particularly limited by clayey texture, wetness, and firmness of subsoils.

ROOT FORMS IN 6-INCH PINE-SITE HARDWOODS

To illustrate root forms of the major pine-site hardwoods, Manwiller and Koch[1] excavated three trees of 22 species (tables 3-1 and 16-3) 5.5 to 6.5 inches in dbh, plus a single Shumard oak of similar size. All of the trees were selected where southern pines were also growing. Most came from central Louisiana, but northern red oak was sampled in west-central Arkansas and scarlet oak and chestnut oak came from northern Alabama. Black oak was obtained from both Arkansas and Alabama. To confine data to material potentially available for utilization as chips by existing or forseeable equipment, the portion of the stump-root system considered was limited to that within a radius of 3 feet from the tree center—no information was obtained on portions of roots beyond this limit. The trees averaged 6.0 inches in dbh, 50.7 feet in total length, with a stem length of 37.6 feet, stump-root length of 4.2 feet, and stem top diameter of 1.8 inch (table 16-3). Hickory and black tupelo trees had the longest stump-root systems, 6.2 and 6.0 feet, respectively. Winged elm and yellow-poplar had shallowest roots, 3.0 and 3.1 feet deep.

Figures 14-4 through 14-26 illustrate the great diversity of these root systems. It is clear why harvesting the central root mass by first severing laterals and then pulling the stump-taproot is more difficult with hickory and black tupelo than with the southern pines. Trees of these species have deep laterals (figs. 14-8 and 14-25) that strongly resist extraction by the equipment shown in figures 16-32 and 16-33.

Figures 14-4 through 14-26 are arranged alphabetically by species common name (see sugarberry for hackberry sp.). Each figure illustrates roots from three 6-inch trees grown on pine sites, except for Shumard oak which is illustrated by a single tree. Those on the left have lateral roots trimmed to a 3-foot radius, while those on the right are trimmed to a 1-foot radius. In each figure, all photos are at the same scale; see 1-foot scale mark on each. Each of the six photos comprising each figure has two values noted; the first value is the green weight of the stump-root system expressed as a percentage of the green weight of the stem (including bark); the value in parentheses is a comparable statistic based on ovendry weights. Tables 14-1AB give green weights in pounds and tables 14-2AB ovendry weights in pounds, together with component percentages of complete biomass tree weight, for each species.

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[1] Manwiller, F. G. and P. Koch. 1981. Some properties of roots of 6-inch hardwood trees of 22 species that grow on southern pine sites—and distribution of biomass in such trees. Final Report FS-SO-3201-1.59, dated September 23, 1981, on file at the Southern Forest Experiment Station, Forest Service, U.S. Dep. Agric., Pineville, LA, 41 p.

GREEN ASH

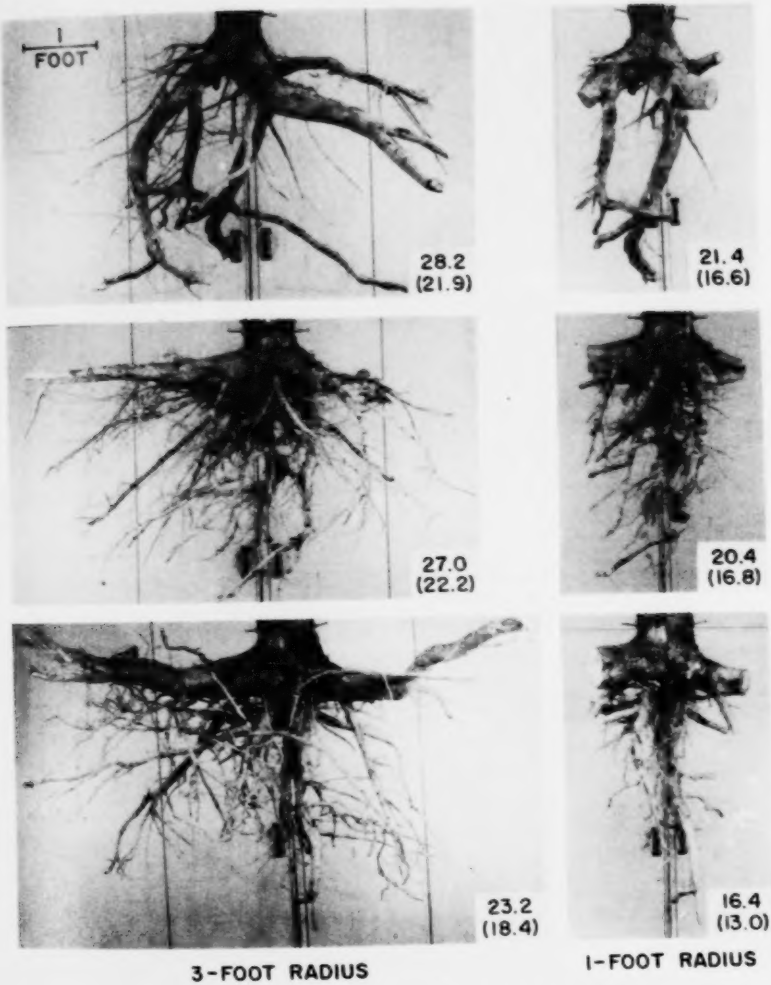

1 FOOT
28.2
(21.9)
21.4
(16.6)
27.0
(22.2)
20.4
(16.8)
23.2
(18.4)
16.4
(13.0)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-4.—Green ash. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

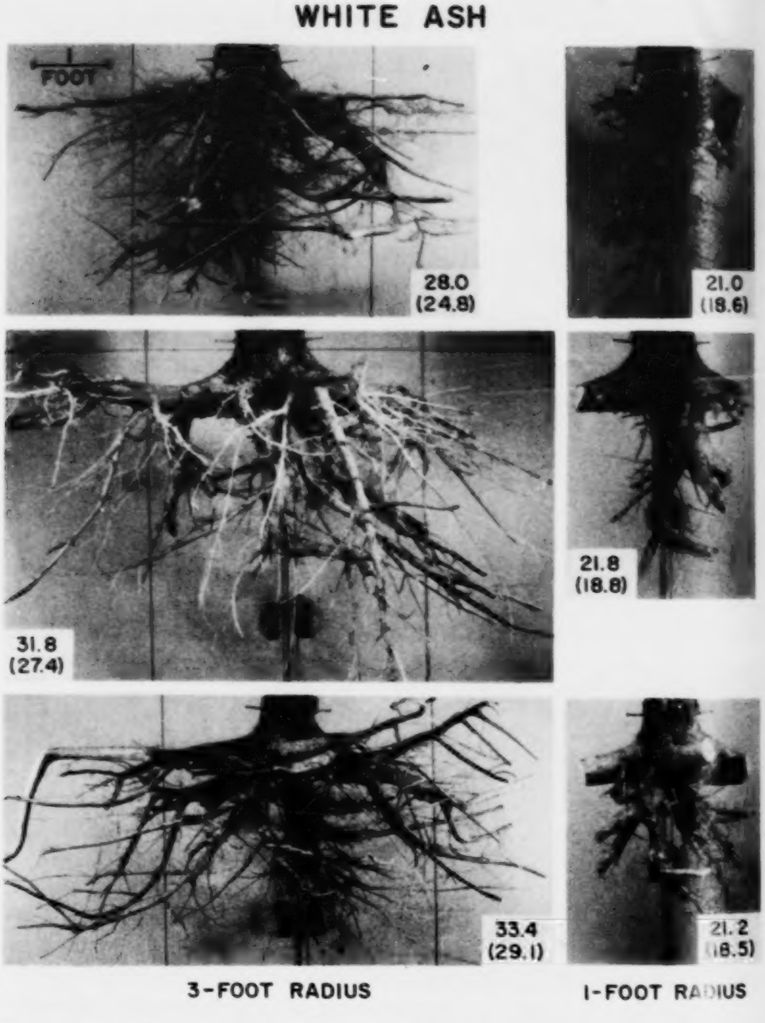

WHITE ASH
FOOT
28.0
(24.8)
21.0
(18.6)
31.8
(27.4)
21.8
(18.8)
33.4
(29.1)
21.2
(18.5)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-5.—White ash. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

AMERICAN ELM

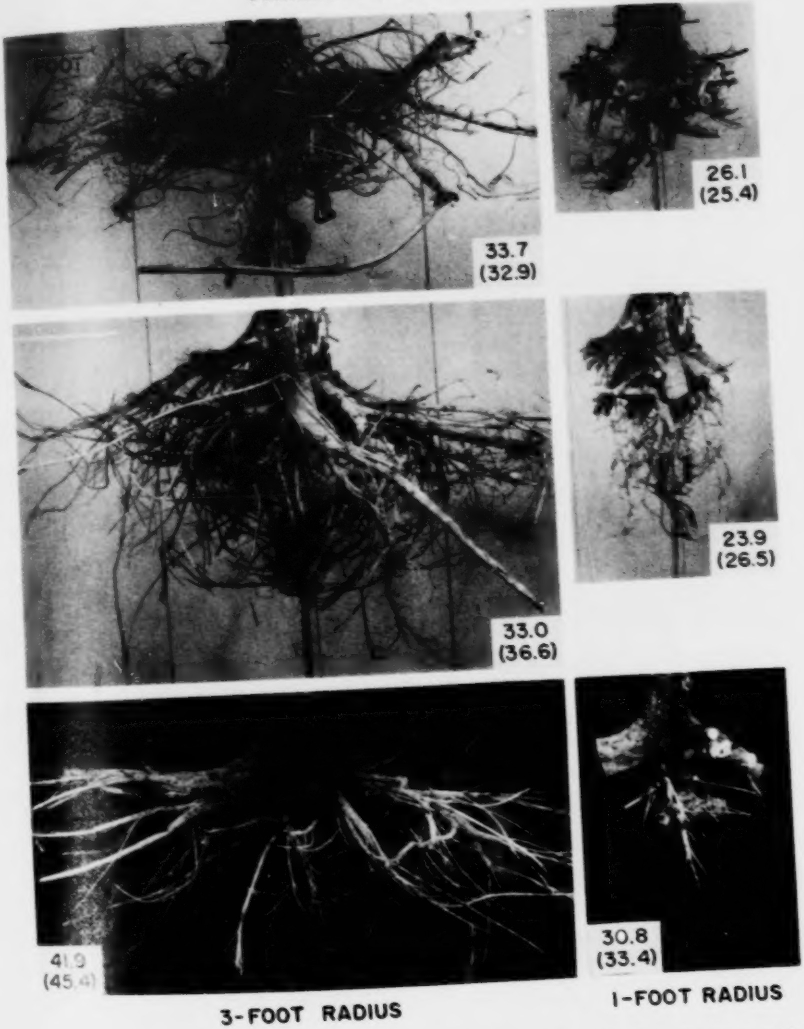

33.7
(32.9)
26.1
(25.4)
33.0
(36.6)
23.9
(26.5)
41.9
(45.4)
30.8
(33.4)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-6.—American elm. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

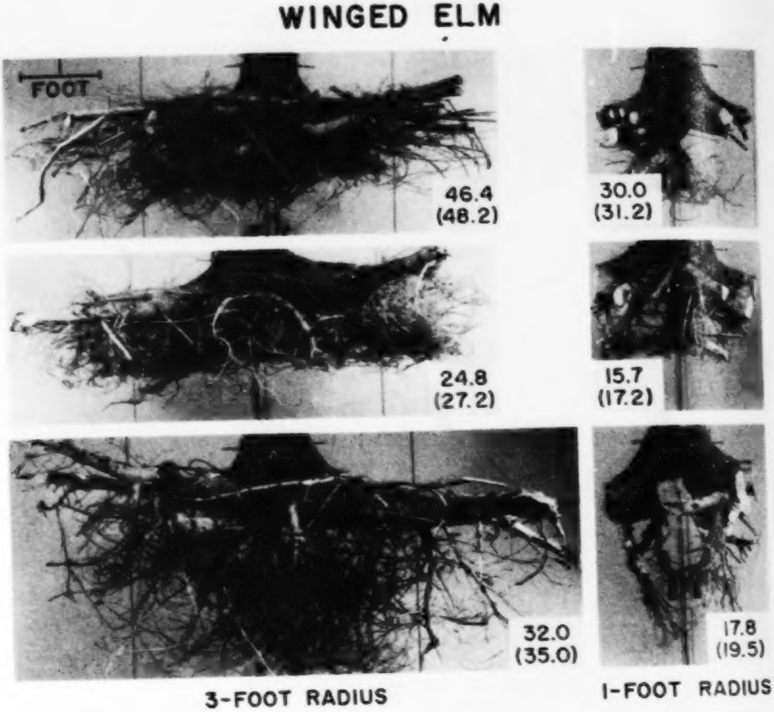
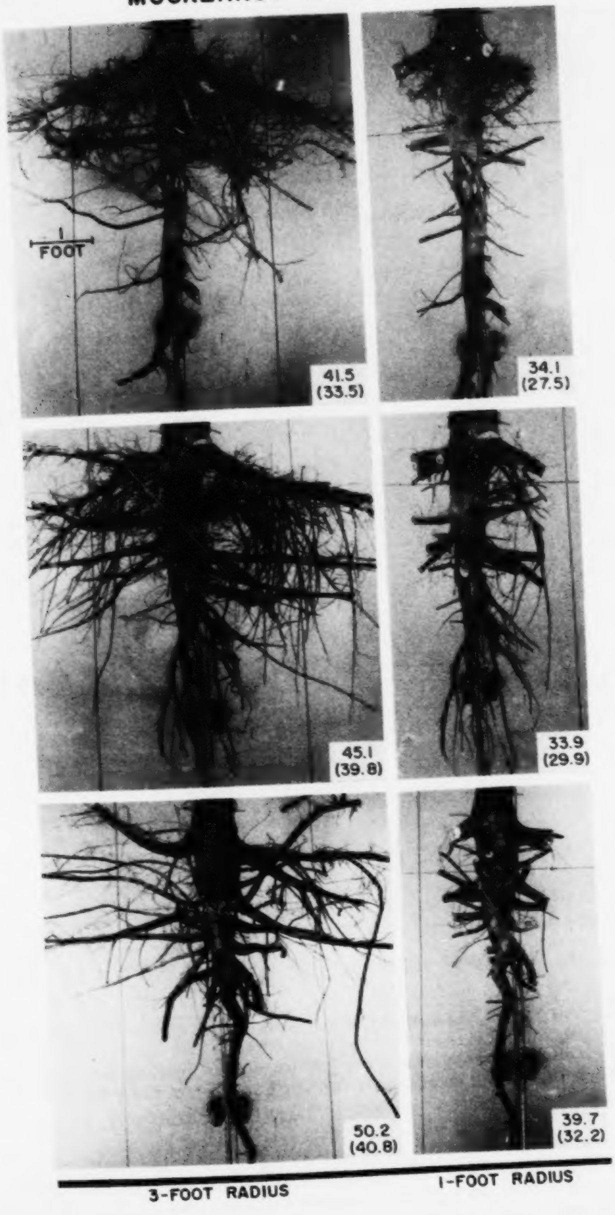

WINGED ELM
FOOT
46.4
(48.2)
30.0
(31.2)
24.8
(27.2)
15.7
(17.2)
32.0
(35.0)
17.8
(19.5)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-7.—Winged elm. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.



MOCKERNUT HICKORY

1 FOOT
41.5
(33.5)
34.1
(27.5)
45.1
(39.8)
33.9
(29.9)
50.2
(40.8)
39.7
(32.2)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-8.—Mockernut hickory. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

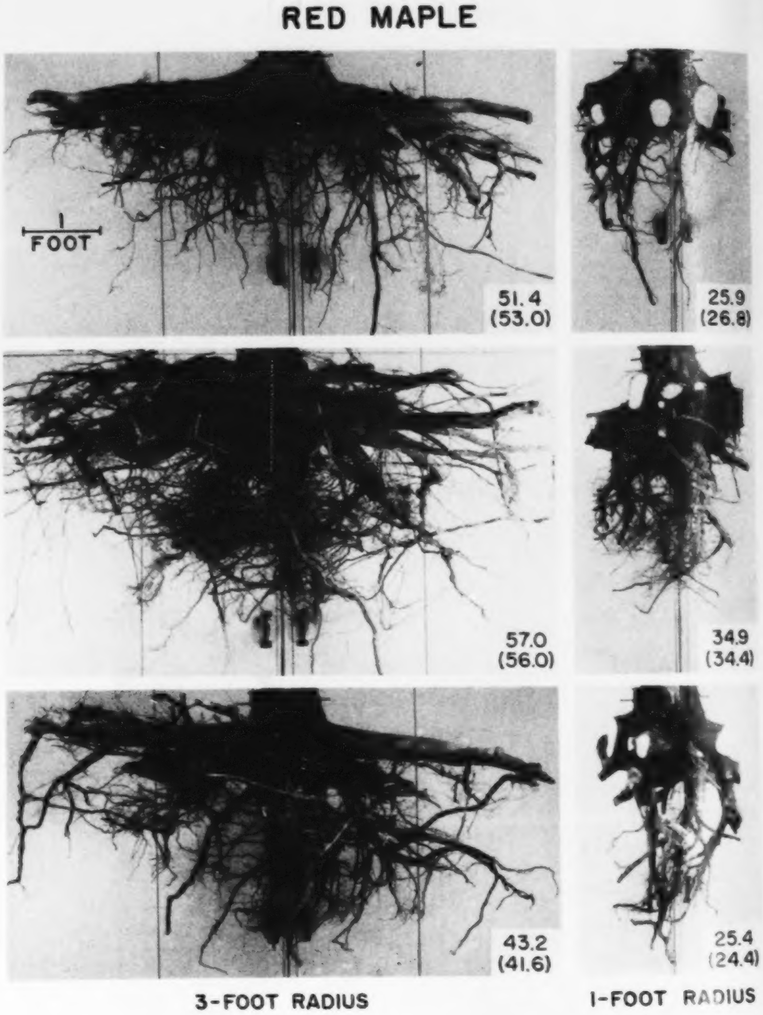

RED MAPLE
1 FOOT
51.4
(53.0)
25.9
(26.8)
57.0
(56.0)
34.9
(34.4)
43.2
(41.6)
25.4
(24.4)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-9.—Red maple. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

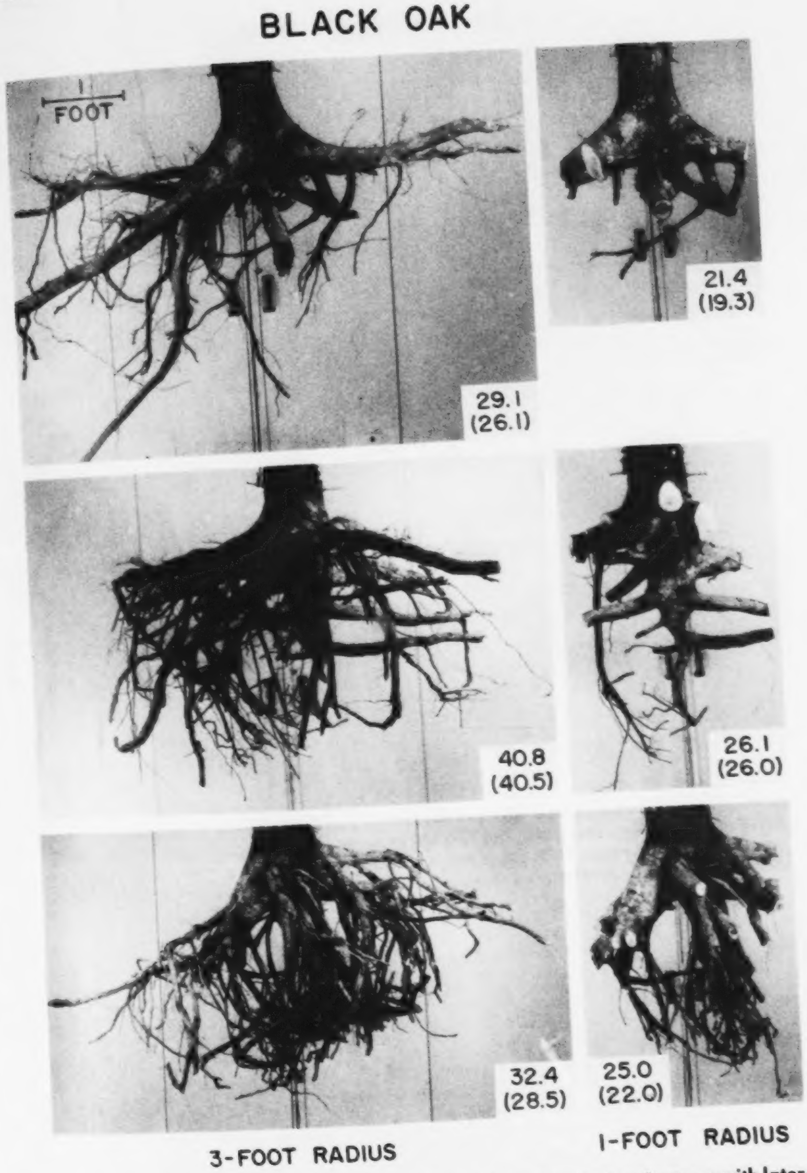

BLACK OAK
1 FOOT
29.1
(26.1)
21.4
(19.3)
40.8
(40.5)
26.1
(26.0)
32.4
(28.5)
25.0
(22.0)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-10.—Black oak. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

BLACKJACK OAK

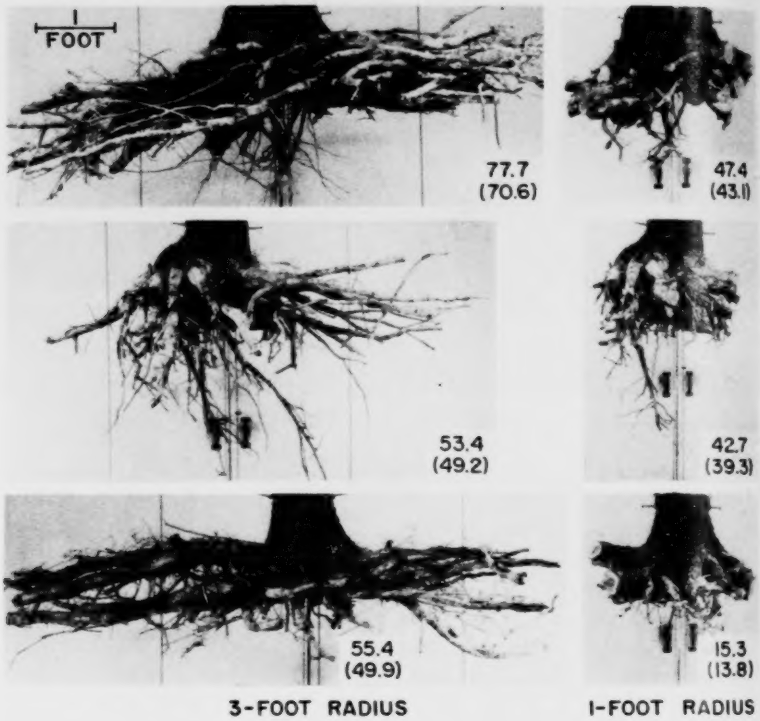

1 FOOT
77.7
(70.6)
47.4
(43.1)
53.4
(49.2)
42.7
(39.3)
55.4
(49.9)
15.3
(13.8)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-11.—Blackjack oak. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

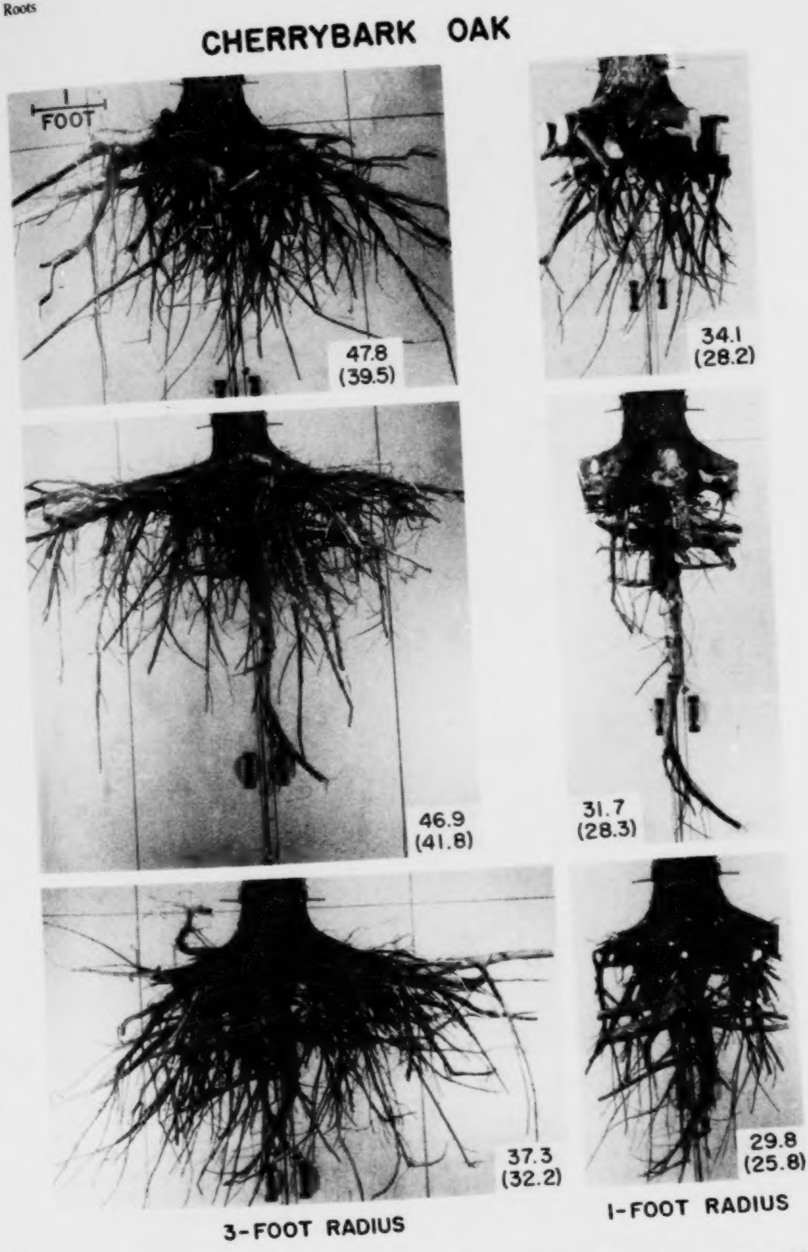

CHERRYBARK OAK
1 FOOT
47.8
(39.5)
34.1
(28.2)
46.9
(41.8)
31.7
(28.3)
37.3
(32.2)
29.8
(25.8)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-12.—Cherrybark oak. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

CHESTNUT OAK

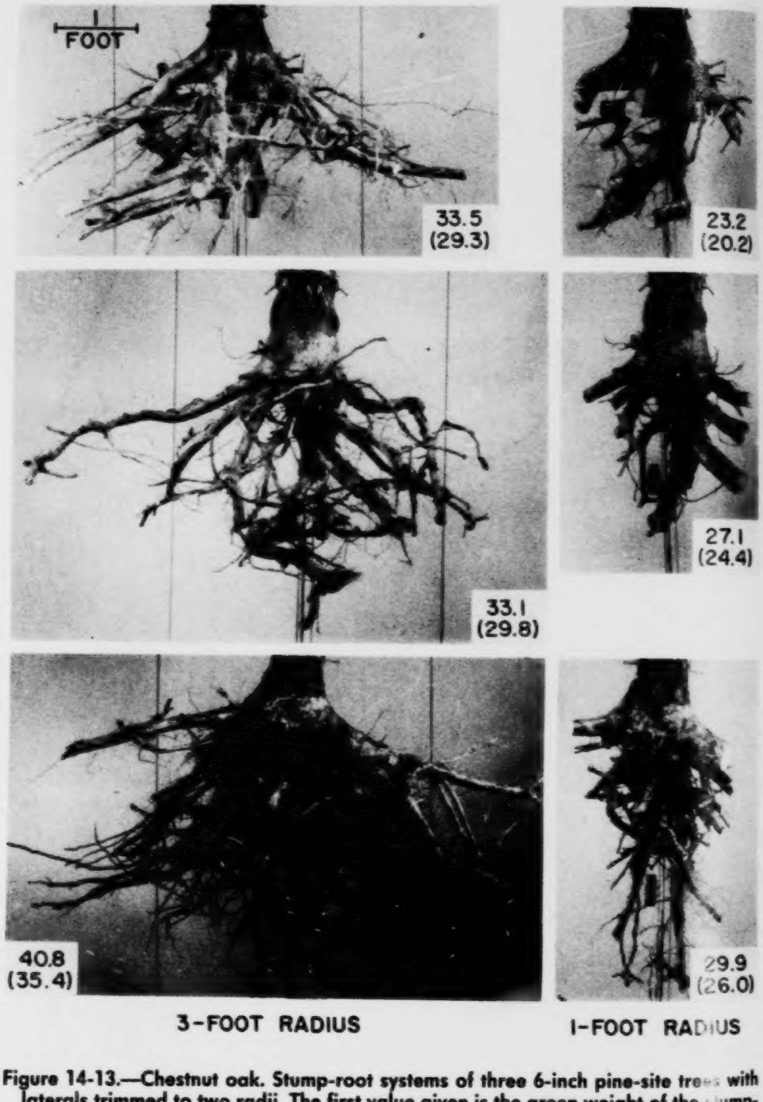

1 FOOT
33.5
(29.3)
23.2
(20.2)
33.1
(29.8)
27.1
(24.4)
40.8
(35.4)
29.9
(26.0)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-13.—Chestnut oak. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weight.

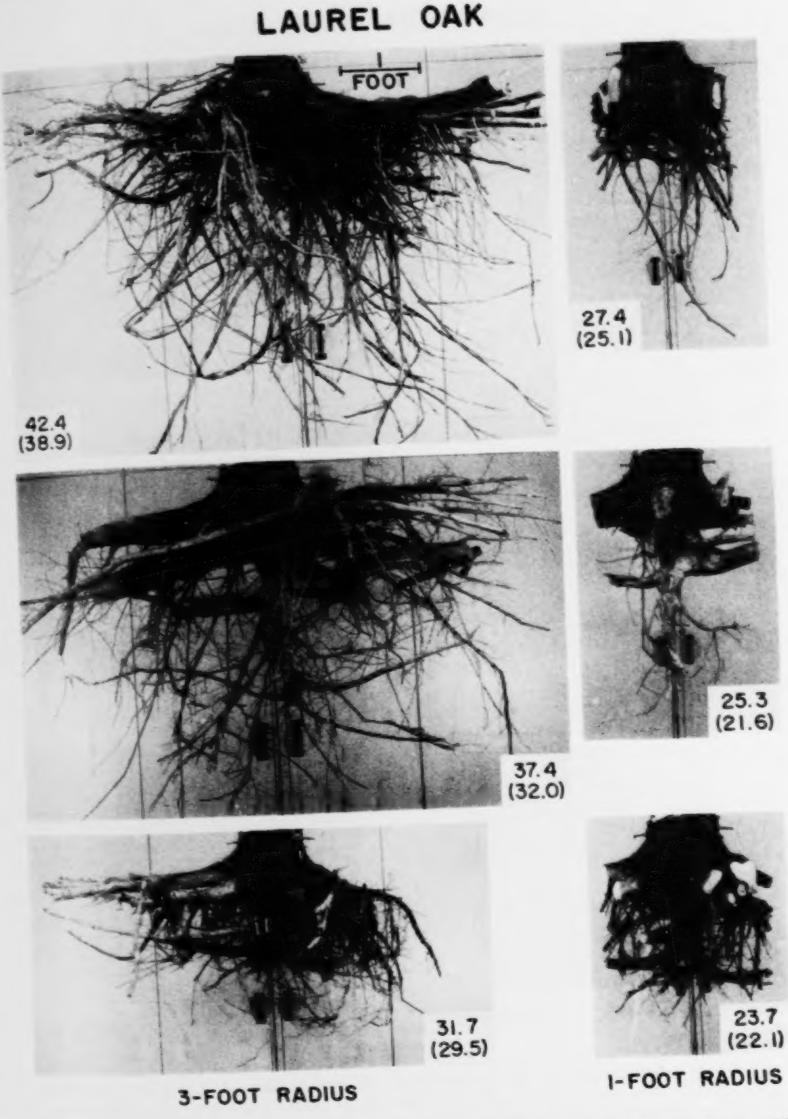

LAUREL OAK
FOOT
42.4
(38.9)
27.4
(25.1)
37.4
(32.0)
25.3
(21.6)
31.7
(29.5)
23.7
(22.1)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-14.—Laurel oak. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

NORTHERN RED OAK

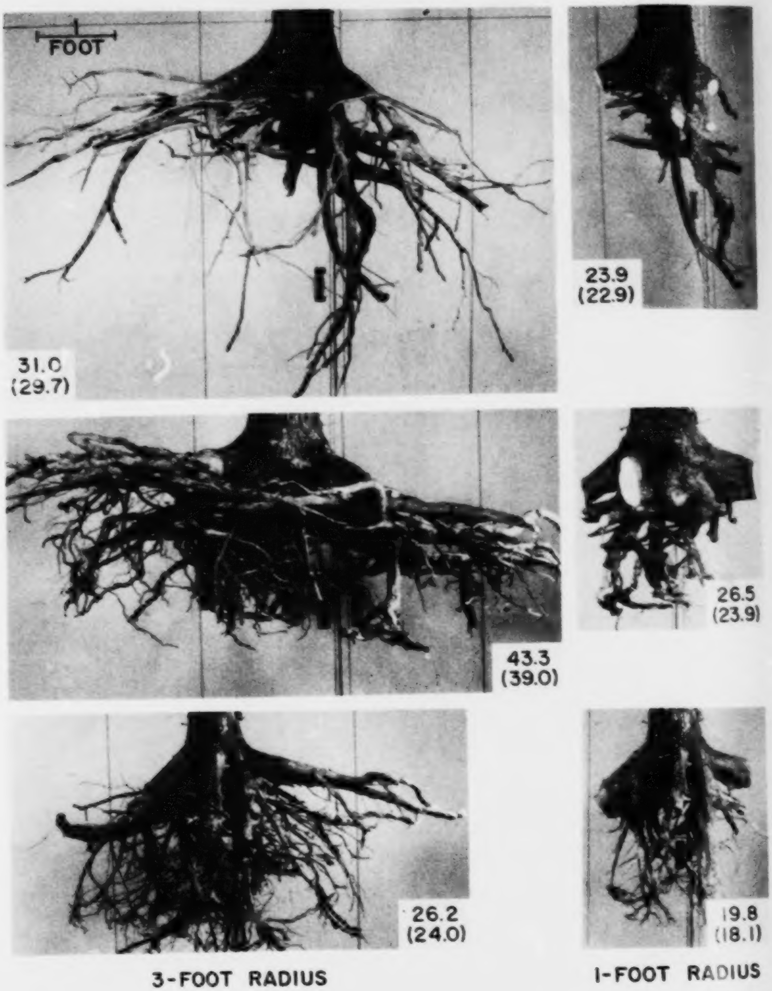

FOOT
31.0
(29.7)
23.9
(22.9)
43.3
(39.0)
26.5
(23.9)
26.2
(24.0)
19.8
(18.1)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-15.—Northern red oak. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

POST OAK

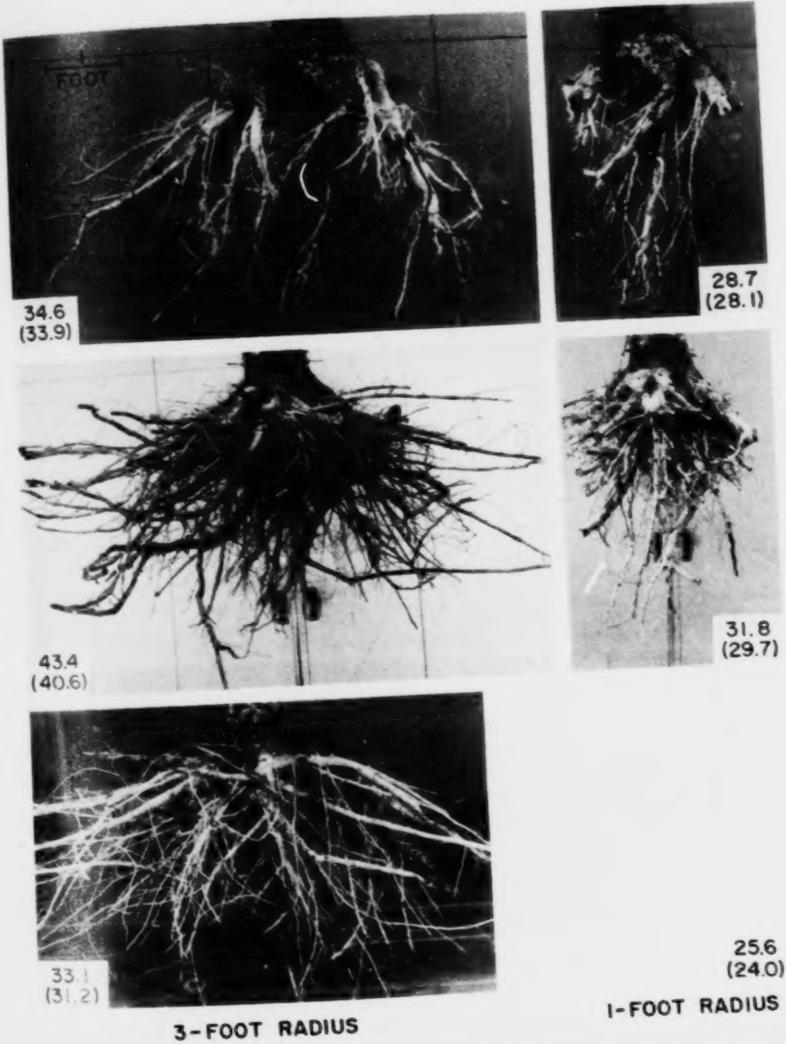

1
FOOT
34.6
(33.9)
28.7
(28.1)
43.4
(40.6)
31.8
(29.7)
33.1
(31.2)
25.6
(24.0)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-16.—Post oak. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

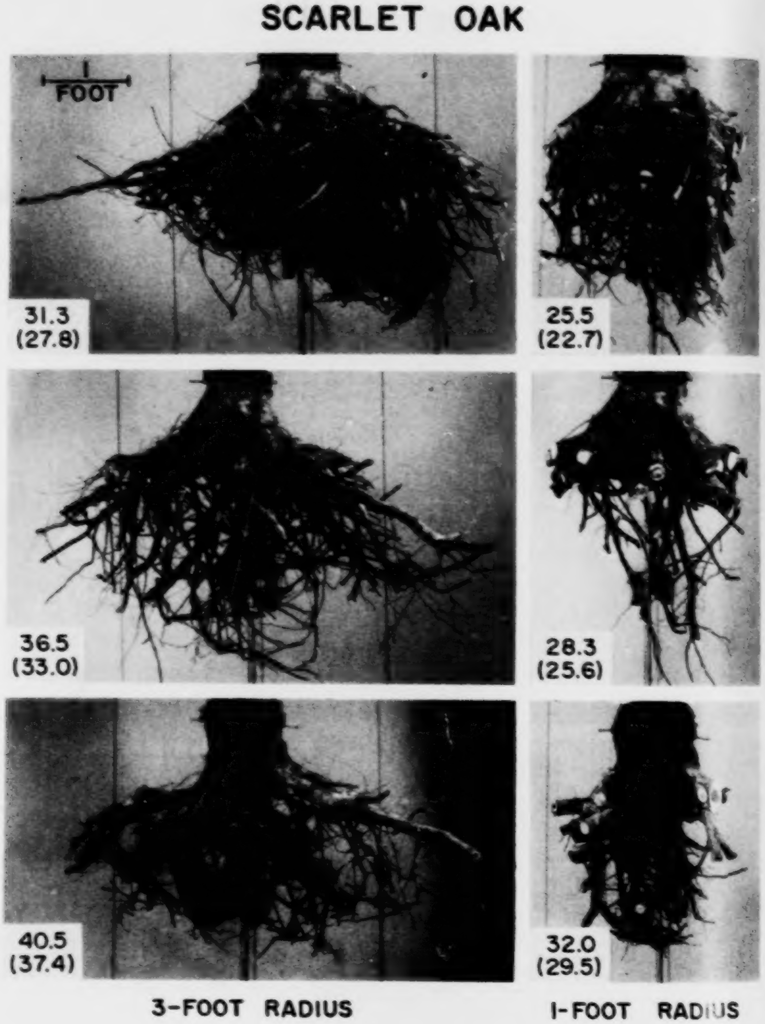

SCARLET OAK
1 FOOT
31.3
(27.8)
25.5
(22.7)
36.5
(33.0)
28.3
(25.6)
40.5
(37.4)
32.0
(29.5)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-17.—Scarlet oak. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

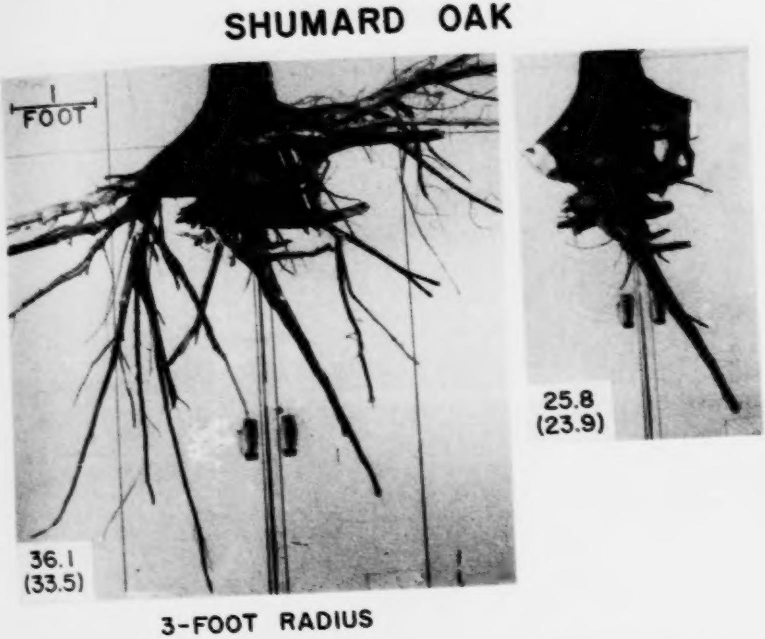

SHUMARD OAK
1
FOOT
36.1
(33.5)
25.8
(23.9)
3-FOOT RADIUS

Figure 14-18.—Shumard oak. Stump-root systems of a 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

SOUTHERN RED OAK

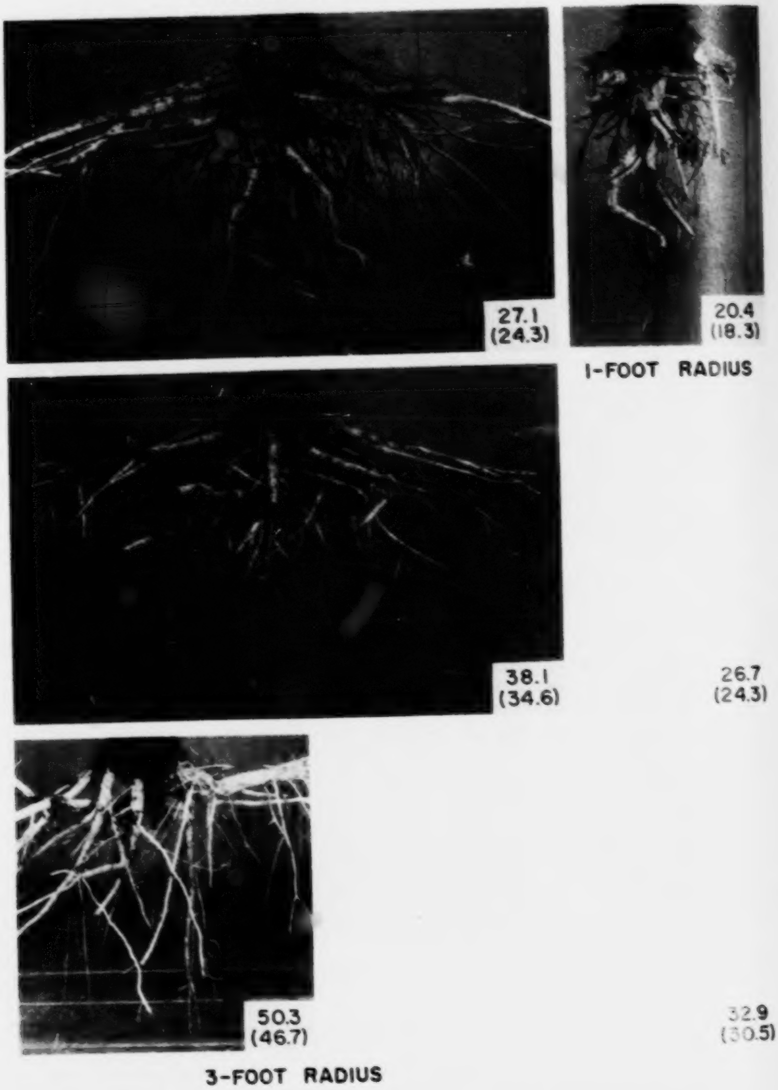

27.1
(24.3)
20.4
(18.3)
1-FOOT RADIUS
38.1
(34.6)
26.7
(24.3)
50.3
(46.7)
32.9
(30.5)
3-FOOT RADIUS

Figure 14-19.—Southern red oak. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to 3-foot radius and one to 1-foot radius. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

WATER OAK

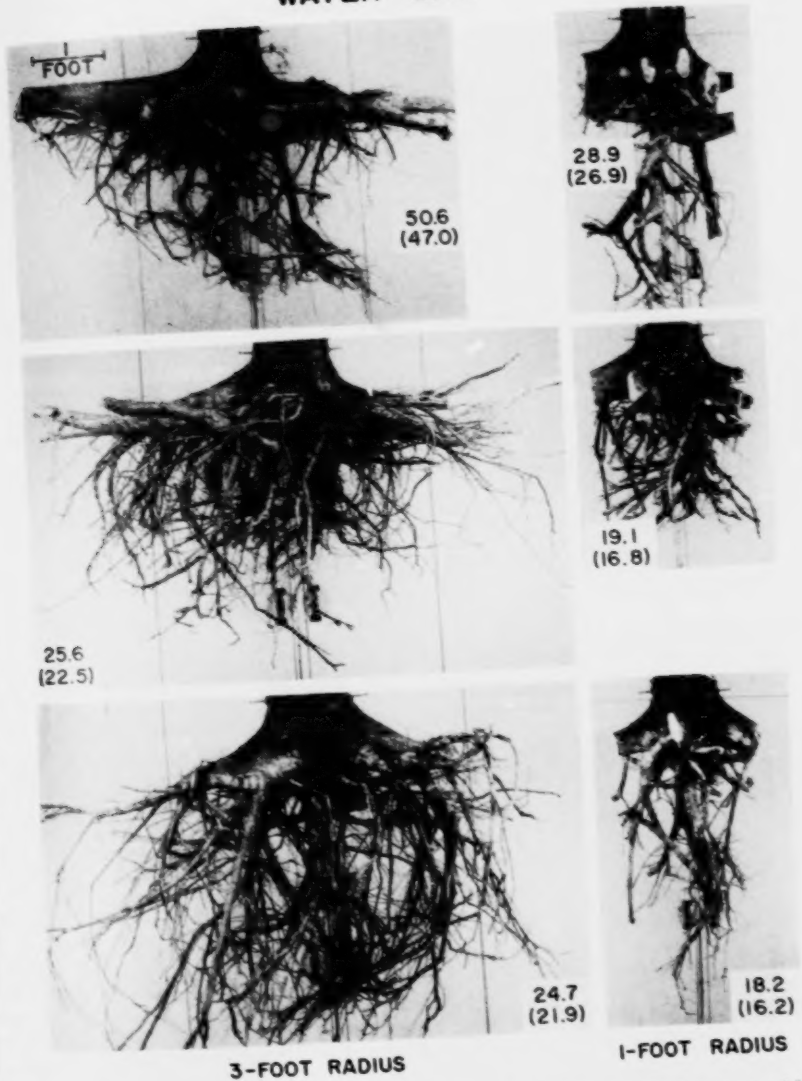

1 FOOT
50.6
(47.0)
28.9
(26.9)
25.6
(22.5)
19.1
(16.8)
24.7
(21.9)
18.2
(16.2)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-20.—Water oak. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights

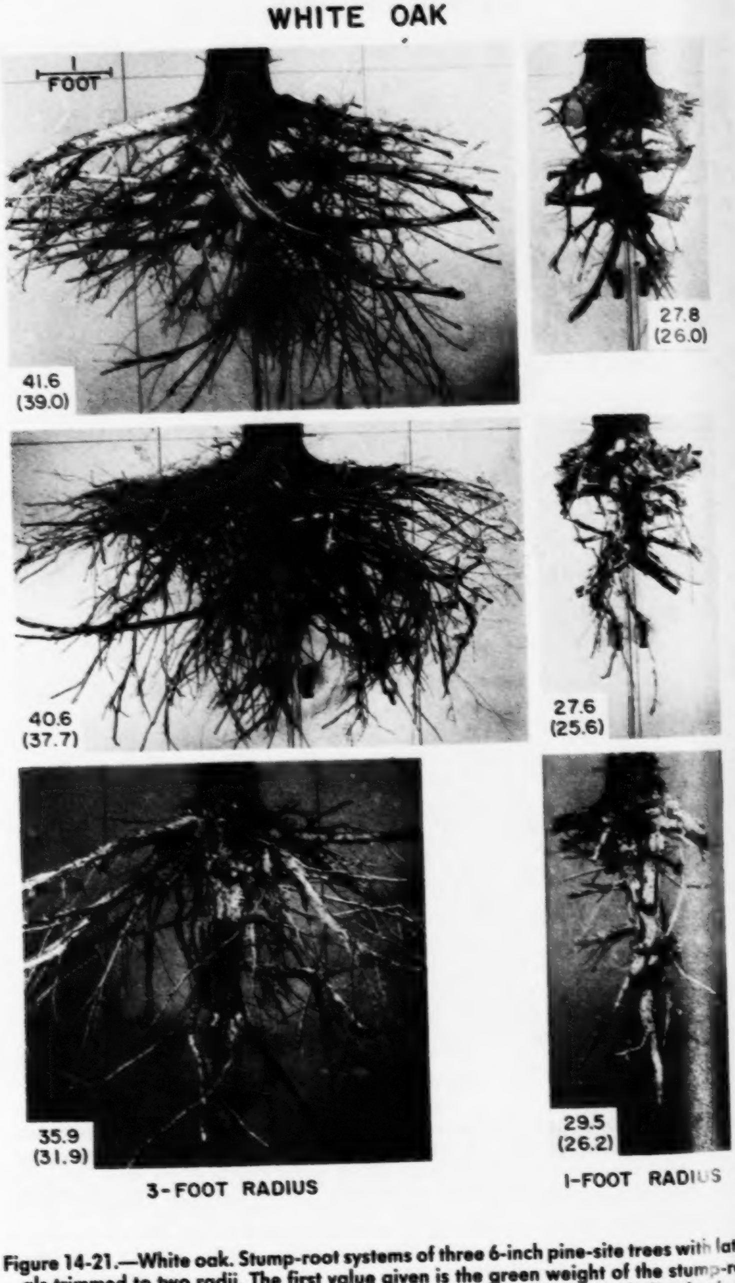
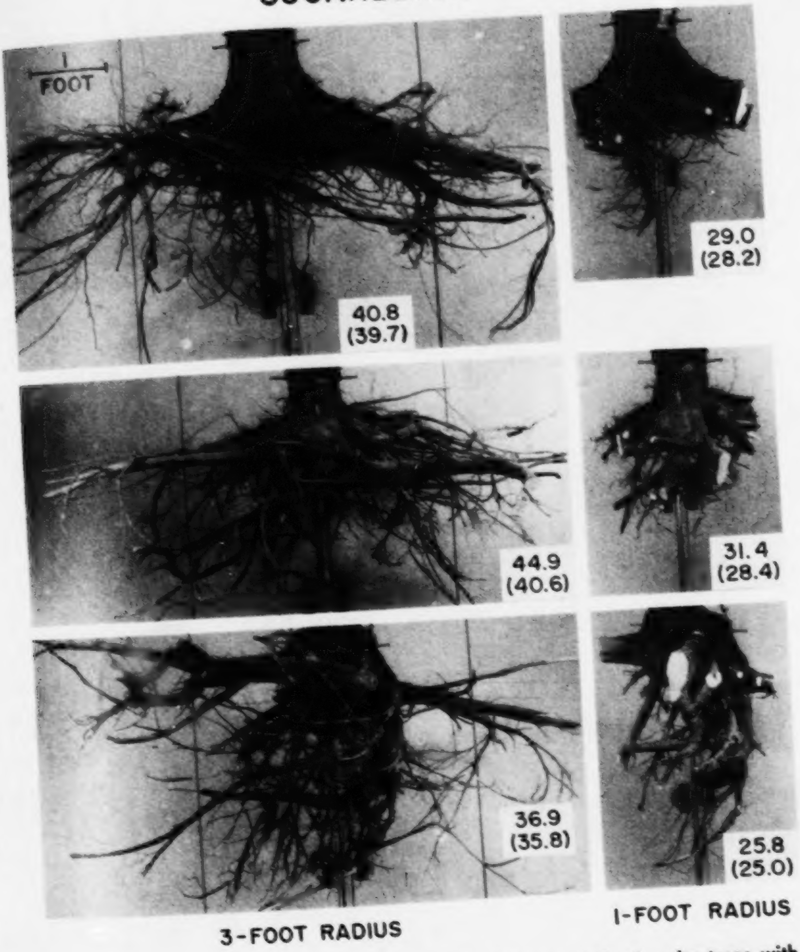

WHITE OAK
1 FOOT
41.6
(39.0)
27.8
(26.0)
40.6
(37.7)
27.6
(25.6)
35.9
(31.9)
29.5
(26.2)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-21.—White oak. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.



SUGARBERRY

1 FOOT
40.8
(39.7)
29.0
(28.2)
44.9
(40.6)
31.4
(28.4)
36.9
(35.8)
25.8
(25.0)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-22.—Sugarberry. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

SWEETBAY

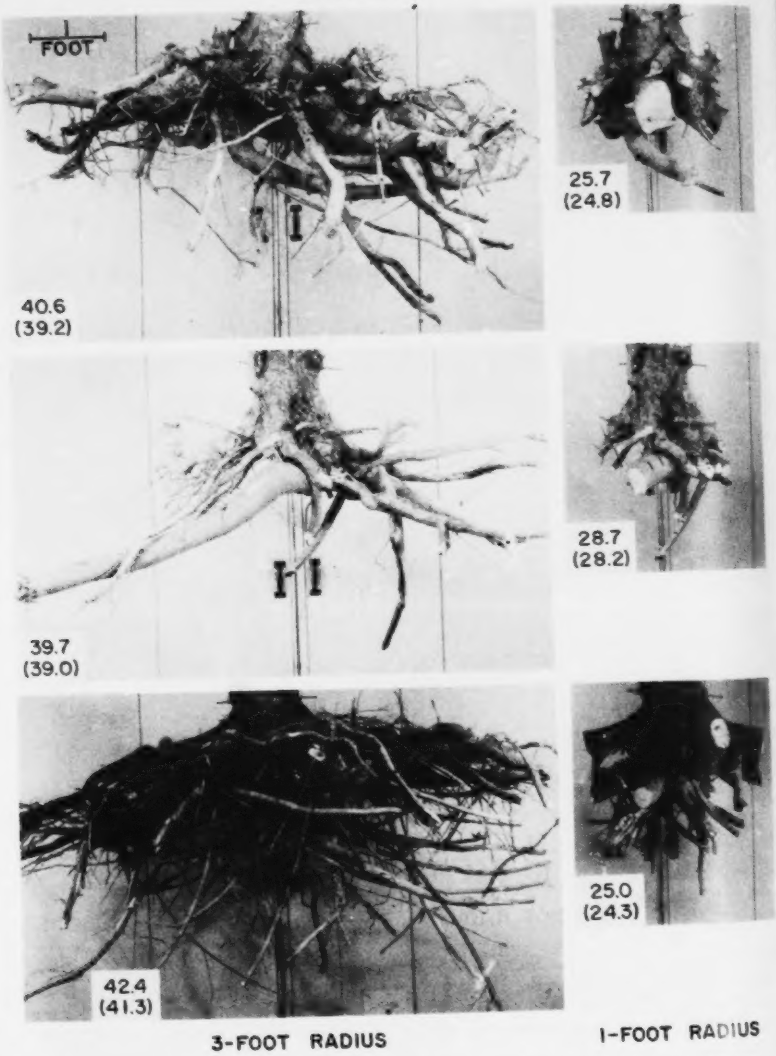

FOOT
40.6
(39.2)
25.7
(24.8)
39.7
(39.0)
28.7
(28.2)
42.4
(41.3)
25.0
(24.3)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-23.—Sweetbay. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

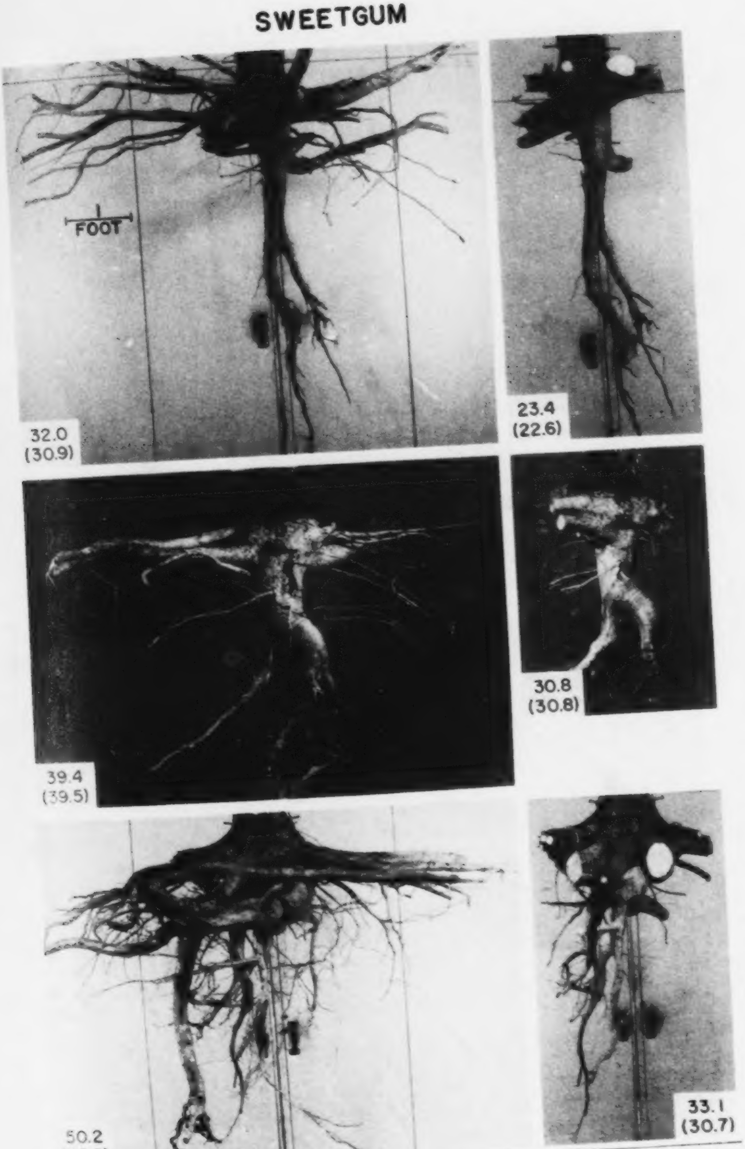

SWEETGUM
FOOT
32.0
(30.9)
23.4
(22.6)
39.4
(39.5)
30.8
(30.8)
50.2
(46.6)
33.1
(30.7)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-24.—Sweetgum. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

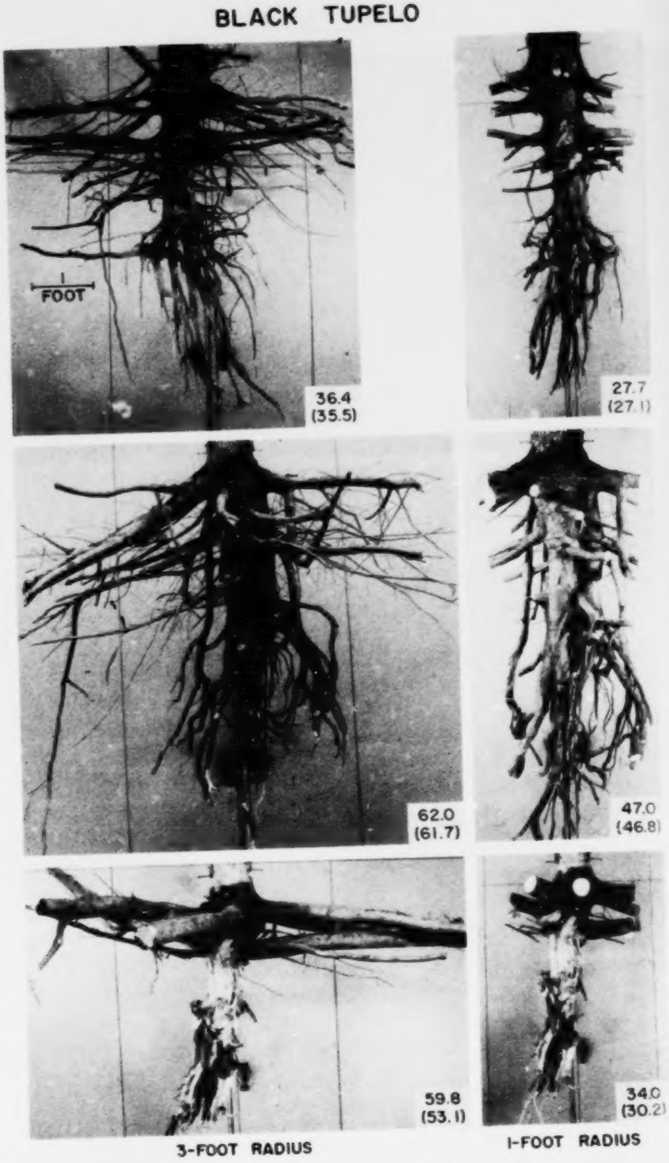

BLACK TUPELO
FOOT
36.4
(35.5)
27.7
(27.1)
62.0
(61.7)
47.0
(46.8)
59.8
(53.1)
34.0
(30.2)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-25.—Black tupelo. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

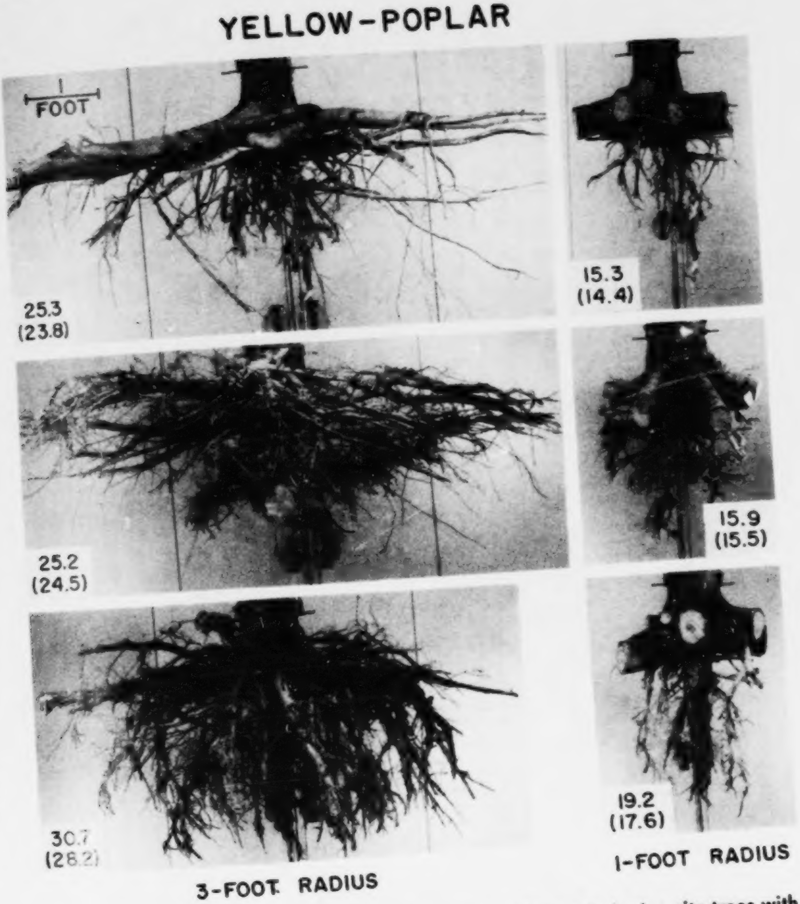

YELLOW-POPLAR
1 FOOT
25.3
(23.8)
15.3
(14.4)
25.2
(24.5)
15.9
(15.5)
30.7
(28.2)
19.2
(17.6)
3-FOOT RADIUS
1-FOOT RADIUS

Figure 14-26.—Yellow-poplar. Stump-root systems of three 6-inch pine-site trees with laterals trimmed to two radii. The first value given is the green weight of the stump-root system expressed as a percentage of the green weight of the stem, including bark; the value in parentheses is a comparable statistic based on ovendry weights.

TABLE 14-1A.—*Green weights of 6-inch pine-site hardwood trees of 22 species, and their percentages of complete-tree green biomass[1]; lateral roots severed at 3-foot radius* (Manwiller and Koch, see text footnote 1)

Species	Complete tree		Stem: wood and bark[2]		Branches: wood and bark[3]		Twigs[4]		Foliage		Wood and bark in central stump-root[5]	
	Lb	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*
Ash, green	299.2	*100*	205.3	*69.6*	26.6	*7.1*	7.7	*2.5*	7.1	*2.4*	52.6	*18.3*
Ash, white	407.3	*100*	248.9	*61.2*	47.1	*11.4*	18.3	*4.6*	15.9	*3.9*	77.0	*19.0*
Elm, American	400.3	*100*	234.3	*58.7*	47.2	*11.4*	19.7	*4.7*	15.8	*3.8*	83.3	*21.4*
Elm, winged	439.9	*100*	258.2	*57.3*	60.1	*14.3*	28.0	*6.6*	11.8	*2.8*	81.8	*19.0*
Hackberry, sp.[6]	302.7	*100*	173.8	*56.9*	33.2	*11.3*	15.5	*5.3*	10.4	*3.4*	69.6	*23.1*
Hickory, sp.	381.1	*100*	211.4	*56.1*	42.2	*10.5*	16.4	*4.2*	14.6	*3.7*	96.6	*25.4*
Maple, red	578.8	*100*	224.0	*38.6*	160.6	*27.9*	51.6	*8.8*	31.2	*5.4*	111.4	*19.3*
Oak, black	387.6	*100*	250.0	*64.9*	26.7	*6.7*	12.8	*3.2*	12.9	*3.3*	85.1	*21.9*
Oak, blackjack	417.3	*100*	171.1	*41.9*	88.3	*20.1*	33.6	*8.5*	14.6	*3.6*	109.5	*25.8*
Oak, cherrybark	374.4	*100*	204.7	*54.7*	35.3	*9.4*	27.1	*7.2*	17.8	*4.7*	89.4	*24.0*
Oak, chestnut	440.8	*100*	266.2	*60.6*	45.0	*9.9*	18.7	*4.2*	15.8	*3.6*	95.0	*21.7*
Oak, laurel	406.7	*100*	244.4	*60.2*	36.1	*8.8*	24.8	*6.1*	10.4	*2.6*	91.0	*22.3*
Oak, northern red	503.1	*100*	310.8	*62.5*	58.7	*11.3*	14.0	*2.8*	13.6	*2.7*	106.0	*20.8*

TABLE 14-1A.—*Green weights of 6-inch pine-site hardwood trees of 22 species, and their percentages of complete-tree green biomass*[1]*; lateral roots severed at 3-foot radius* (Manwiller and Koch, see text footnote 1)—Continued

Species	Complete tree		Stem: wood and bark[2]		Branches: wood and bark[3]		Twigs[4]		Foliage		Wood and bark in central stump-root[5]	
	Lb	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*
Oak, post	422.4	*100*	270.4	*63.9*	31.2	*7.5*	10.8	*2.5*	10.8	*2.6*	99.1	*23.5*
Oak, scarlet	433.4	*100*	268.6	*61.8*	39.6	*8.8*	15.7	*3.7*	15.1	*3.5*	94.3	*22.3*
Oak, southern red	459.9	*100*	266.6	*57.9*	66.0	*14.2*	15.8	*3.5*	13.0	*2.8*	98.4	*21.5*
Oak, water	513.3	*100*	293.5	*59.2*	58.2	*10.7*	40.6	*7.4*	20.8	*3.9*	100.0	*18.8*
Oak, white	540.8	*100*	302.2	*56.2*	66.3	*12.2*	31.8	*5.9*	20.4	*3.5*	120.1	*22.1*
Sweetbay	426.5	*100*	224.4	*51.5*	62.5	*15.7*	26.1	*6.5*	20.9	*5.2*	92.6	*21.2*
Sweetgum	392.7	*100*	233.0	*59.1*	26.9	*6.8*	17.6	*4.6*	21.7	*5.7*	93.5	*23.8*
Tupelo, black	448.3	*100*	221.8	*48.5*	68.6	*15.0*	27.1	*6.3*	22.4	*5.2*	108.3	*25.0*
Yellow-poplar	342.1	*100*	227.6	*66.7*	15.5	*4.5*	18.4	*5.3*	19.0	*5.4*	61.6	*18.0*

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[1] Each value is the average for three trees. Percents represent that component's proportion of the complete tree. Apparent small discrepancies between a component weight and its percent arise because each is an independent average of the three trees.

[2] From a point 6 inches above the ground to the point where the central stem could no longer be distinguished or to a 0.5-inch minimum diameter.

[3] Branches 0.5 inch in diameter and larger.

[4] Smaller than 0.5 inch in diameter.

[5] From a point 6 inches above the ground to the bottom of the root system.

[6] Sugarberry.

TABLE 14-1B.—*Green component weights of 6-inch pine-site hardwood trees of 22 species, and their percentages of complete-tree green biomass*[1]*; lateral roots severed at a 1-foot radius* (Manwiller and Koch, see text footnote 1)

Species	Complete tree		Stem: wood and bark[2]		Branches: wood and bark[3]		Twigs[4]		Foliage		Wood and bark in central stump-root[5]	
	Lb	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*
Ash, green	285.2	*100*	205.3	*73.1*	26.6	*7.5*	7.7	*2.7*	7.1	*2.5*	38.6	*14.2*
Ash, white	383.5	*100*	248.9	*65.0*	47.1	*12.0*	18.3	*4.9*	15.9	*4.2*	53.2	*13.9*
Elm, American	378.9	*100*	234.3	*62.3*	47.2	*12.0*	19.7	*4.9*	15.8	*4.0*	62.0	*16.8*
Elm, winged	408.0	*100*	258.2	*61.8*	60.1	*15.5*	28.0	*7.1*	11.8	*3.0*	49.9	*12.6*
Hackberry, sp.[6]	281.9	*100*	173.8	*61.0*	33.2	*12.1*	15.5	*5.7*	10.4	*3.7*	48.9	*17.4*
Hickory, sp.	360.5	*100*	211.4	*59.3*	42.2	*11.2*	16.4	*4.4*	14.6	*4.0*	76.0	*21.2*
Maple, red	530.5	*100*	224.0	*42.1*	160.6	*30.4*	51.6	*9.7*	31.2	*5.9*	63.1	*11.9*
Oak, black	362.6	*100*	250.0	*69.2*	26.7	*7.2*	12.8	*3.4*	12.9	*3.5*	60.1	*16.7*
Oak, blackjack	371.8	*100*	171.1	*47.8*	88.3	*22.5*	33.6	*9.8*	14.6	*4.1*	64.1	*15.8*
Oak, cherrybark	350.0	*100*	204.7	*58.6*	35.3	*10.0*	27.1	*7.7*	17.8	*5.0*	65.1	*18.7*
Oak, chestnut	416.5	*100*	266.2	*64.1*	45.0	*10.5*	18.7	*4.4*	15.8	*3.8*	70.7	*17.2*
Oak, laurel	378.0	*100*	244.4	*64.7*	36.1	*9.4*	24.8	*6.6*	10.4	*2.8*	62.3	*16.5*
Oak, northern red	470.6	*100*	310.8	*66.7*	58.7	*11.9*	14.0	*3.0*	13.6	*2.8*	73.5	*15.5*
Oak, post	400.2	*100*	270.4	*67.4*	31.2	*7.9*	10.8	*2.7*	10.8	*2.7*	76.9	*19.2*

TABLE 14-1B.—*Green component weights of 6-inch pine-site hardwood trees of 22 species, and their percentages of complete-tree green biomass*[1]*; lateral roots severed at a 1-foot radius* (Manwiller and Koch, see text footnote 1)—Continued

Species	Complete tree		Stem: wood and bark[2]		Branches: wood and bark[3]		Twigs[4]		Foliage		Wood and bark in central stump-root[5]	
	Lb	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*
Oak, scarlet	414.1	*100*	268.6	*64.7*	39.6	*9.1*	15.7	*3.9*	15.1	*3.7*	75.0	*18.5*
Oak, southern red	430.3	*100*	266.6	*61.9*	66.0	*15.3*	15.8	*3.7*	13.0	*3.0*	68.8	*16.1*
Oak, water	478.4	*100*	293.5	*62.9*	58.2	*11.5*	40.6	*8.0*	20.8	*4.1*	65.3	*13.5*
Oak, white	505.9	*100*	302.2	*59.9*	66.3	*13.0*	31.8	*6.4*	20.4	*3.8*	85.2	*17.0*
Sweetbay	392.2	*100*	224.4	*55.9*	62.5	*16.9*	26.1	*7.0*	20.9	*5.6*	58.2	*14.7*
Sweetgum	367.3	*100*	233.0	*63.4*	26.9	*7.3*	17.6	*5.0*	21.7	*6.0*	68.1	*18.4*
Tupelo, black	416.5	*100*	221.8	*52.3*	68.6	*16.2*	27.1	*6.9*	22.4	*5.7*	76.5	*18.9*
Yellow-poplar	318.8	*100*	227.6	*71.6*	15.5	*4.8*	18.4	*5.7*	19.0	*5.8*	38.3	*12.0*

[1] Each value is the average for three trees. Percents represent that component's proportion of the complete tree. Apparent small discrepancies between a component weight and its percent arise because each is an independent average of the three trees.

[2] From a point 6 inches above the ground to the point where the central stem could no longer be distinguished or to a 0.5-inch minimum diameter.

[3] Branches 0.5 inch in diameter and larger.

[4] Smaller than 0.5 inch in diameter.

[5] From a point 6 inches above the ground to the bottom of the root system.

[6] Sugarberry.

TABLE 14-2A.—*Ovendry component weights of 6-inch pine-site hardwood trees of 22 species, and their percentages of complete-tree weight*[1]*; lateral roots severed at 3-foot radius* (Manwiller and Koch, see text footnote 1)

Species	Complete tree		Stem: wood and bark[2]		Branches: wood and bark[3]		Twigs[4]		Foliage		Wood and bark in central stump-root[5]	
	Lb	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*
Ash, green	179.7	*100*	130.3	*73.7*	15.9	*7.1*	4.4	*2.4*	2.5	*1.4*	26.5	*15.4*
Ash, white	262.4	*100*	169.0	*64.4*	28.6	*10.8*	11.5	*4.4*	7.6	*2.9*	45.6	*17.4*
Elm, American	214.7	*100*	125.4	*58.6*	26.2	*11.9*	10.5	*4.7*	5.3	*2.4*	47.2	*22.5*
Elm, winged	266.3	*100*	152.5	*56.0*	36.9	*14.5*	17.8	*6.9*	6.9	*2.7*	52.3	*20.0*
Hackberry, sp.[6]	180.8	*100*	104.4	*57.3*	20.7	*11.6*	10.0	*5.7*	5.9	*3.3*	39.8	*22.1*
Hickory, sp.	220.7	*100*	131.2	*60.1*	25.2	*10.9*	9.0	*3.9*	5.4	*2.4*	50.0	*22.7*
Maple, red	320.3	*100*	127.0	*39.6*	87.3	*27.4*	29.1	*9.0*	14.3	*4.5*	62.6	*19.6*
Oak, black	221.9	*100*	146.0	*66.3*	16.9	*7.4*	7.4	*3.2*	5.2	*2.3*	46.4	*20.8*
Oak, blackjack	244.7	*100*	99.8	*41.6*	55.7	*21.8*	23.5	*10.3*	7.1	*3.0*	58.4	*23.4*
Oak, cherrybark	221.4	*100*	126.1	*57.1*	21.9	*9.8*	16.0	*7.1*	9.9	*4.4*	47.5	*21.6*
Oak, chestnut	258.8	*100*	164.4	*63.7*	26.4	*10.0*	10.2	*3.9*	6.2	*2.4*	51.6	*20.0*
Oak, laurel	235.9	*100*	144.0	*61.2*	22.6	*9.4*	15.7	*6.7*	5.2	*2.2*	48.3	*20.4*
Oak, northern red	290.8	*100*	182.4	*63.5*	36.7	*12.1*	8.5	*3.0*	5.7	*1.9*	57.4	*19.5*
Oak, post	237.7	*100*	155.3	*65.2*	17.8	*7.5*	6.0	*2.6*	4.4	*1.8*	54.2	*22.8*

TABLE 14-2A.—*Ovendry component weights of 6-inch pine-site hardwood trees of 22 species, and their percentages of complete-tree weight*[1]*; lateral roots severed at 3-foot radius* (Manwiller and Koch, see text footnote 1)—Continued

Species	Complete tree		Stem: wood and bark[2]		Branches: wood and bark[3]		Twigs[4]		Foliage		Wood and bark in central stump-root[5]	
	Lb	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*
Oak, scarlet	239.6	*100*	152.5	*63.5*	23.1	*9.2*	9.1	*3.8*	6.4	*2.7*	48.5	*20.8*
Oak, southern red	257.2	*100*	152.0	*59.0*	39.1	*15.0*	9.0	*3.6*	6.1	*2.4*	51.0	*20.0*
Oak, water	297.6	*100*	174.0	*60.7*	33.7	*10.6*	25.7	*8.0*	10.6	*3.4*	53.6	*17.3*
Oak, white	307.6	*100*	177.5	*58.2*	39.6	*12.8*	15.9	*5.1*	9.4	*2.9*	65.0	*21.0*
Sweetbay	210.8	*100*	112.9	*52.3*	31.6	*16.2*	13.6	*6.9*	7.4	*3.7*	45.3	*20.9*
Sweetgum	179.6	*100*	107.7	*59.9*	14.2	*7.8*	8.2	*4.7*	7.5	*4.3*	42.0	*23.2*
Tupelo, black	223.7	*100*	116.7	*51.2*	30.6	*13.7*	13.8	*6.4*	8.1	*3.7*	54.4	*25.1*
Yellow-poplar	163.5	*100*	112.5	*68.9*	7.4	*4.5*	8.6	*5.3*	6.2	*3.7*	28.8	*17.6*

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[1] Each value is the average for three trees. Percents represent that component's proportion of the complete tree. Apparent small discrepancies between a component weight and its percent arise because each is an independent average of the three trees.

[2] From a point 6 inches above the ground to the point where the central stem could no longer be distinguished or to a 0.5-inch minimum diameter.

[3] Branches 0.5 inch in diameter and larger.

[4] Smaller than 0.5 inch in diameter.

[5] From a point 6 inches above the ground to the bottom of the root system.

[6] Sugarberry.

TABLE 14-2B.—*Ovendry component weights of 6-inch pine-site hardwood trees of 22 species, and their percentages of complete-tree weight*[1]*; lateral roots severed at 1-foot radius* (Manwiller and Koch, see text footnote 1)

Species	Complete tree		Stem: wood and bark[2]		Branches: wood and bark[3]		Twigs[4]		Foliage		Wood and bark in central stump-root[5]	
	Lb	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*
Ash, green	172.6	*100*	130.3	*76.7*	15.9	*7.4*	4.4	*2.5*	2.5	*1.5*	19.5	*11.9*
Ash, white	248.2	*100*	169.0	*68.2*	28.6	*11.4*	11.5	*4.7*	7.6	*3.0*	31.5	*12.7*
Elm, American	202.5	*100*	125.4	*62.2*	26.2	*12.6*	10.5	*4.9*	5.3	*2.5*	35.1	*17.7*
Elm, winged	245.9	*100*	152.5	*60.7*	36.9	*15.7*	17.8	*7.5*	6.9	*2.9*	31.8	*13.3*
Hackberry, sp.[6]	168.9	*100*	104.4	*61.3*	20.7	*12.4*	10.0	*6.1*	5.9	*3.5*	28.0	*16.6*
Hickory, sp.	210.0	*100*	131.2	*63.1*	25.2	*11.5*	9.0	*4.1*	5.4	*2.5*	39.3	*18.7*
Maple, red	293.1	*100*	127.0	*43.2*	87.3	*29.9*	29.1	*9.8*	14.3	*5.0*	35.4	*12.2*
Oak, black	208.1	*100*	146.0	*70.5*	16.9	*7.9*	7.4	*3.5*	5.2	*2.4*	32.7	*15.7*
Oak, blackjack	220.3	*100*	99.8	*46.8*	55.7	*24.0*	23.5	*11.6*	7.1	*3.3*	34.1	*14.2*
Oak, cherrybark	208.4	*100*	126.1	*60.8*	21.9	*10.4*	16.0	*7.5*	9.9	*4.6*	34.5	*16.7*
Oak, chestnut	245.7	*100*	164.4	*67.1*	26.4	*10.5*	10.2	*4.1*	6.2	*2.5*	38.5	*15.8*
Oak, laurel	220.6	*100*	144.0	*65.4*	22.6	*10.1*	15.7	*7.1*	5.2	*2.4*	33.0	*15.0*
Oak, northern red	273.2	*100*	182.4	*67.5*	36.7	*12.8*	8.5	*3.2*	5.7	*2.0*	39.9	*14.5*
Oak, post	225.5	*100*	155.3	*68.7*	17.8	*8.0*	6.0	*2.7*	4.4	*1.9*	42.0	*18.6*
Oak, scarlet	229.7	*100*	152.5	*66.3*	23.1	*9.6*	9.1	*4.0*	6.4	*2.8*	38.6	*17.2*

TABLE 14-2B.—*Ovendry component weights of 6-inch pine-site hardwood trees of 22 species, and their percentages of complete-tree weight*[1]*; lateral roots severed at 1-foot radius* (Manwiller and Koch, see text footnote 1)—Continued

Species	Complete tree		Stem: wood and bark[2]		Branches: wood and bark[3]		Twigs[4]		Foliage		Wood and bark in central stump-root[5]	
	Lb	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*	*Lb*	*Pct*
Oak, southern red	241.9	*100*	152.0	*62.7*	39.1	*16.1*	9.0	*3.8*	6.1	*2.6*	35.7	*14.8*
Oak, water	279.0	*100*	174.0	*64.1*	33.7	*11.4*	25.7	*8.5*	10.6	*3.6*	35.0	*12.4*
Oak, white	288.6	*100*	177.5	*61.8*	39.6	*13.6*	15.9	*5.4*	9.4	*3.1*	46.1	*16.1*
Sweetbay	193.9	*100*	112.9	*56.7*	31.6	*17.4*	13.6	*7.4*	7.4	*4.0*	28.4	*14.5*
Sweetgum	168.2	*100*	107.7	*64.0*	14.2	*8.3*	8.2	*5.1*	7.5	*4.6*	30.6	*18.0*
Tupelo, black	207.7	*100*	116.7	*55.1*	30.6	*14.8*	13.8	*6.9*	8.1	*4.0*	38.4	*19.1*
Yellow-poplar	152.6	*100*	112.5	*73.8*	7.4	*4.9*	8.6	*5.7*	6.2	*4.0*	17.9	*11.7*

[1] Each value is the average for three trees. Percents represent that component's proportion of the complete tree. Apparent small discrepancies between a component weight and its percent arise because each is an independent average of the three trees.

[2] From a point 6 inches above the ground to the point where the central stem could no longer be distinguished or to a 0.5-inch minimum diameter.

[3] Branches 0.5 inch in diameter and larger.

[4] Smaller than 0.5 inch in diameter.

[5] From a point 6 inches above the ground to the bottom of the root system.

[6] Sugarberry.

14-3 STUMP-ROOT WEIGHTS AND PROPORTION OF TREE WEIGHTS

SIX-INCH PINE-SITE HARDWOODS

Figures 14-4 through 14-26 and the explanatory text in the preceding subsection ROOT FORMS OF 6-INCH HARDWOODS, and tables 3-1 and 16-3 describe trees collected by Manwiller and Koch[1]. A trench was hand excavated around each selected tree, the lateral roots were severed at a 3-foot radius from the center of the stem, and the tree uprooted with a truck-mounted winch. The exposed root was cleaned with hand tools. Field measurements included: dbh; total tree length, including root; stem length from a point 6 inches above the ground to the point where the central axial stem could no longer be distinguished (or to a minimum diameter of 0.5 inch); length of stump root system from a point 6 inches above ground to the bottom of the root system; and stem top diameter (the diameter at point of division into branches or 0.5-inch minimum for trees with a central stem). In the field a portable balance was used to obtain green weights of twigs (0.5-inch-diameter maximum), branches, leaves, and stem. All twigs and leaves were placed in paper bags and brought to the laboratory for ovendrying.

Two-inch-thick disks were taken from each branch beginning at a point 2 feet from its junction with the stem on another branch and every 4 feet thereafter. Similarly, 2-inch-thick disks were removed from the stem at 4-foot intervals beginning 2 feet above the stump, weighed green, and then brought to the laboratory and ovendried.

The entire stump-root system was brought to the laboratory where it was hosed free of dirt, photographed (left side of figs. 14-4 through 14-26), and its green weight recorded. Beginning 6 inches below the top of the stump, pairs of disks, each 2 inches thick, were marked off every foot along the main root. Similar pairs of disks were marked every foot along each lateral beginning 6 inches from the main root.

The laterals were then cut back to a 1-foot radius. The root was again photographed (right side of figs. 14-4 through 14-26), and its green weight recorded. The disk pairs which had been previously marked were then removed from the main root and laterals. One of each pair of disks was ovendried for moisture content determination, the other set aside for measurement of stump root properties.

Lateral roots were severed first at the 3-foot radius because material outside that radius would be too small for commercial significance. The roots were then cut back to 1-foot radius because this portion of the root system can be extracted with commercially available equipment (figs. 16-32 and 16-33).

Leaves, twigs, branch disks, stem disks, and root disks were ovendried. Moisture content of the tree parts, total green and dry weight of the tree, its parts, and their percentages of the whole were calculated from these data (tables 14-1AB and 14-2AB). Gross tree dimensions are given in table 16-3.

Components of biomass.—On a green-weight basis, complete trees with roots severed at a 3-foot radius averaged 423.6 pounds in weight, of which 57.6 percent was in the stem (bark included), 11.6 percent in branches, 5.2 percent in twigs, 3.8 percent in foliage, and 21.8 percent in the stump-root system (table 14-1A). When lateral roots were severed at a 1-foot radius, complete trees averaged 395.5 pounds in weight, of which 61.6 percent was in the stem (bark included), 12.5 percent in branches, 5.6. percent in twigs, 4.1 percent in foliage, and 16.2 percent in the stump-root system (table 14-1B).

On an ovendry-weight basis, complete trees with roots severed at a 3-foot radius averaged 238.0 pounds in weight, of which 59.2 percent was in the stem (bark included), 11.9 percent in branches, 5.4 percent in twigs, 2.9 percent in foliage, and 20.6 percent in the stump-root system (table 14-2A). When lateral roots were severed at 1-foot radius, complete trees averaged 222.9 pounds in weight, of which 63.0 percent was in the stem (bark included), 12.8 percent in branches, 5.7 percent in twigs, 3.1 percent in foliage, and 15.4 percent in the stump-root system (table 14-2B).

Species with the most and least stump-root percentages of complete-tree weight, green and dry, were as follows:

Degree of root trimming and moisture content	Stump-root percentage Most	Least
	Percent	
To a 3-foot radius		
Green	Blackjack oak (25.8)	Yellow-poplar (18.0)
Ovendry	Black tupelo (25.1)	Green ash (15.4)
To a 1-foot radius		
Green	Hickory (21.2)	Red Maple (11.9)
Ovendry	Black Tupelo (19.1)	Yellow-poplar (11.7)

TREES 4 to 12 INCHES IN DBH

With the equipment illustrated in figures 16-32 and 16-33, Sirios (1977) extracted thirty trees of each of four hardwood species from each of two sites (sandy and clay loam) in southern Alabama. Trees measured from 4 to 12 inches in dbh. The harvested portion of the stump-root system averaged 17.9 percent of complete-tree green weight, as follows:

Species and Site	Complete-tree Weight	Stump-root Weight	Stump-root proportion of complete-tree weight
	Pounds		*Percent*
Sweetgum			
Sandy	478	79	16.5
Clay loam	444	84	18.9
Mockernut hickory			
Sandy	577	104	18.0
Clay loam	514	94	18.3
Southern red oak			
Sandy	766	124	16.2
Clay loam	660	94	14.2
White oak			
Sandy	678	164	24.2
Clay loam	532	90	16.9
Average	581	104	17.9

WITHIN-SPECIES VARIATION

The percentages noted in figures 14-4 through 14-26 indicate that even in a single diameter class (e.g., 6-inch), within-species variation in stump-root proportion is considerable.

Young et al. (1963) weighed 20 red maple trees in a range of sizes from 5.6 to 15.8 inches in dbh. These trees, which were sampled in Maine, had stump-root systems that averaged 22.7 percent of complete-tree weight (foliage-free); range in stump-root proportion was from 14.6 to 32.9 percent—green weight basis. No correlation was discernible between dbh and proportion of stump-root biomass. Their data included all roots 1 inch in diameter and larger.

In a study of trees 0.5 to more than 9.5 inches in diameter growing in Tennessee, Harris et al. (1973) found that the smaller trees had a significantly greater proportion of their complete weight in the stump-root system (to a radius of 60 cm) than larger trees, as follows (see table 16-4):

Diameter class	Chestnut oak	Oak-hickory	Yellow-poplar
Inches		*Percent*	
0.5 to 3.5	22.4	18.0	16.9
3.5 to 9.5	14.5	13.7	13.7
>9.5	9.4	9.8	10.7

WEIGHT PER ACRE OF STUMP-ROOT SYSTEMS

Johnson and Risser (1974) measured the weight of stump root systems in a post oak-blackjack oak forest in central Oklahoma; trees were cut as near ground level as possible. Even with these unusually low stumps, stump-root systems constituted 17.8 percent of the biomass (ovendry basis), excluding litter, and weighed 34,812 pounds per acre. In this stand, there were a few old trees up to 28 inches in dbh in a dense canopy of young trees and saplings. Canopy height was 40 to 50 feet; diameters greater than 18 inches were rare.

Weyerhaeuser Company (personal communication 1974) found from a study of a 50-year-old upland hardwood stand in North Carolina that the stump-root systems totalled 40,700 pounds per acre, green-weight basis. There were 220 trees per acre averaging 10 inches in dbh on the sample plots, so each stump-root system had average green weight of 185 pounds.

VOLUME IN STUMPS

Table 27-137 relates volume in stump (not roots) to stump diameter and height.

14-4 ANATOMY

Roots anchor the tree, absorb and conduct water and minerals, and store food. Hyland (1974) listed the ways in which young roots (fig. 14-27 top left) differ from stems, as follows:

- Roots typically lack a pith, the central area being occupied by primary xylem; stems have pith.
- In roots the primary xylem and primary phloem strands are radially arranged, whereas in stems they have collateral arrangement in the vascular bundles.
- The order of development in primary xylem roots is toward the center; in stems it is away from the center.
- Roots typically have an endodermis and a pericycle; stems typically lack these tissues.
- The cortex of roots is wider than that of stems and is much shorter lived.
- The first cork cambium in roots usually originates in the pericycle, that of stems originates in the outer cortex or epidermis.
- Roots possess a root cap and do not bear buds, leaves, or flowers as do stems.
- Lateral roots originate at irregular intervals from the pericycle; stems possess definite nodes, at which buds occur and give rise to leaves or flowers.
- Roots are usually more flexible and are softer than stems.
- Latewood of roots may be less pronounced that that of stems.
- Tracheary elements of roots (i.e., fibers) generally have wider lumens, thinner walls, and larger, more numerous bordered pits than those of stems.
- Walls of tracheary cells are usually less heavily lignified than those of stems.

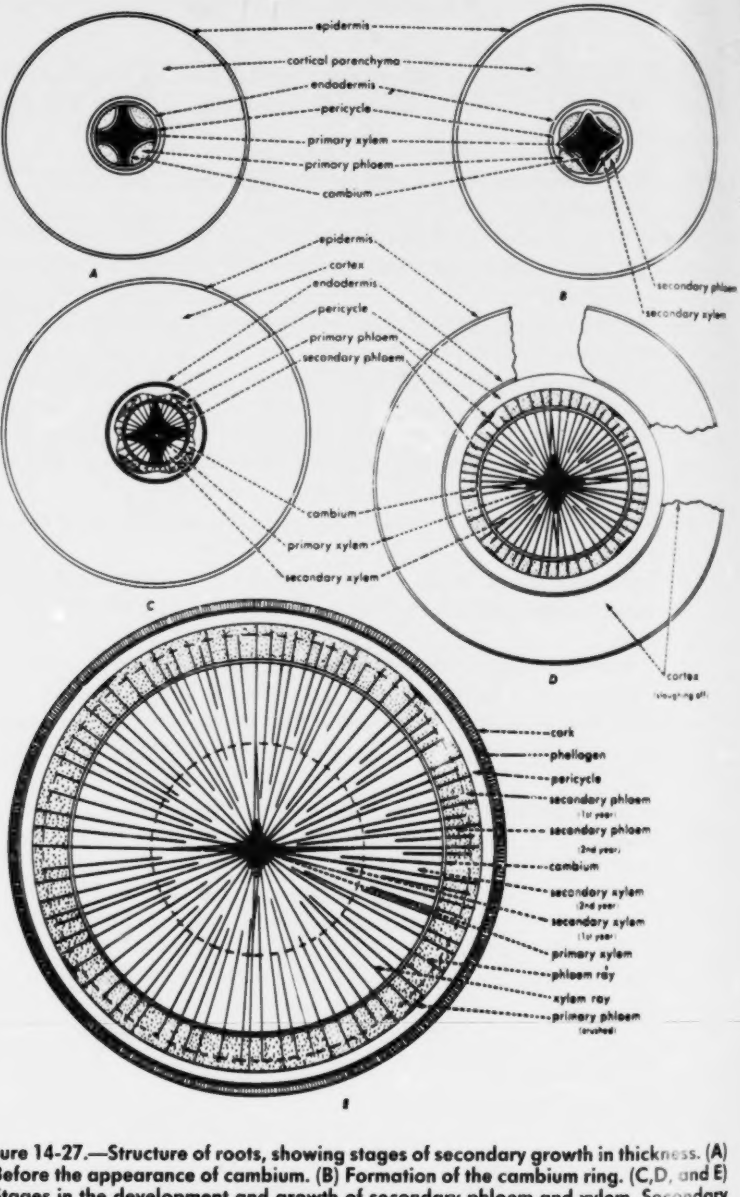
epidermis
cortical parenchyma
endodermis
pericycle
primary xylem
primary phloem
cambium
A
B
secondary phloem
secondary xylem
epidermis
cortex
endodermis
pericycle
primary phloem
secondary phloem
cambium
primary xylem
secondary xylem
C
D
cortex
(sloughing off)
cork
phellogen
pericycle
secondary phloem
(1st year)
secondary phloem
(2nd year)
cambium
secondary xylem
(2nd year)
secondary xylem
(1st year)
primary xylem
phloem ray
xylem ray
primary phloem
(crushed)
E

Figure 14-27.—Structure of roots, showing stages of secondary growth in thickness. (A) Before the appearance of cambium. (B) Formation of the cambium ring. (C,D, and E) Stages in the development and growth of secondary phloem and xylem. Secondary increase in thickness due to the activity of phellogen is also shown. (Drawing after K. Esau in Robbins et al. 1964, by permission of John Wiley and Sons, Inc.)

Roots

The secondary tissues (fig. 14-27 bottom) of roots more closely resemble stemwood tissues, as shown by the following figures (micrographs in figures 14-28 through 14-33 were taken by Arnold Day, State University of New York at Syracuse):

Species	Figure number Stemwood	 Rootwood
Hickory	5-6 bottom and 5-28	14-28
Oak, southern red	5-12 top and 5-39	14-29
Oak, white	5-13 top and 5-41	14-30
Sweetgum	5-14 top and 5-43	14-31
Tupelo, black	5-14 bottom and 5-44	14-32
Yellow-poplar	5-15 and 5-45	14-33

Esau (1977) noted that roots of *Platanus* sp. have a smaller proportion of lignified secondary walls than stems, and a higher proportion of parenchyma tissue. Roots in this species have higher and wider vascular rays than stems and longer parenchyma strands. Vessel diameters are larger and longer in *Platanus* rootwood than in stemwood (Esau 1977).

Cutler (1976) concluded from examination of an extensive collection of microscope slides of hardwood roots at the Royal Botanic Gardens, Kew, Great Britan, that variation in root anatomy is great, and that comparisons between the anatomy of rootwood and stemwood must be made with caution.

Torrey and Feldman (1977) explain the organization and function of the root apex, and Carpenter and Guard (1954) studied the anatomy and morphology of seedling roots of four species of the genus *Quercus*. While industrialists wishing to use roots as raw material are primarily concerned with large roots and stumpwood, the growth habits of typically thin long lateral roots are of interest.

Wilson (1964) found that red maple has horizontal woody roots up to 82 feet long. These roots are characteristically eccentric in cross section, twisted, and only slightly tapered. A study of transverse sections showed that the eccentricities resulted from depressed, often discontinuous, cambial activity opposite the diarch protoxylem poles and that the twisting apparently occurs in the root tips while they grow through the soil. Examination of successive sections from woody roots showed that some growth rings were longitudinally discontinuous, disappearing toward the stem. The presence of both circumferentially and longitudinally discontinuous growth rings makes age determination virtually impossible. Wilson suggested that woody branch roots emerging opposite the protoxylem poles divert materials moving from the stem down the main roots and thus decrease cambial activity further toward the root tip. This reduction could result both in discontinuous growth rings and in the diameter decreases observed after branching. Major factors causing the lack of taper between branch roots may be the relatively rapid rate of extension of the root tips (1.5 to 5 feet per year) and the presence of longitudinally discontinuous growth rings.

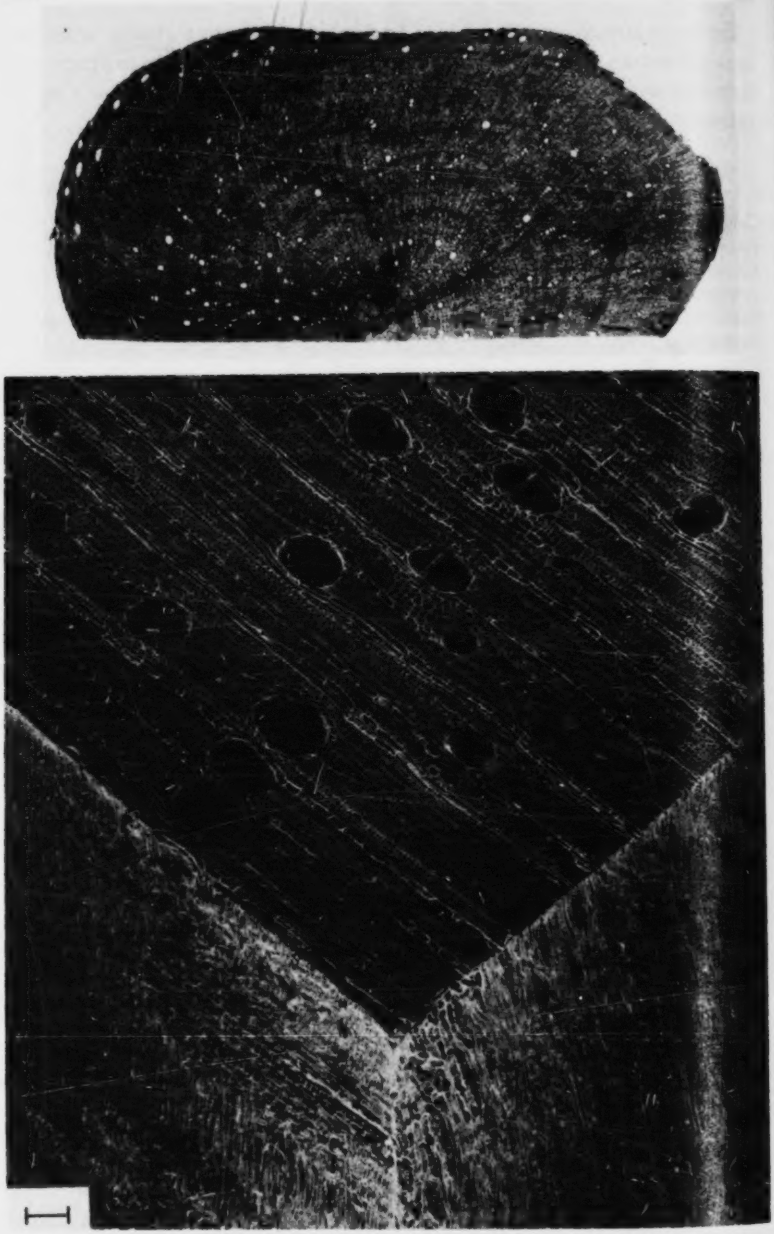

Figure 14-28.—Hickory Rootwood. (Top) Transverse section of root 0.7 inch in diameter. (Bottom) Scanning electron micrograph of transverse section with radial section at left and tangential at right. Compare with true hickory stemwood (fig. 5-28); tyloses are lacking, marginal parenchyma are not obvious, and the rootwood is more semi-ring porous. Scale mark shows 100 micrometers. (Micrographs from files of W.A. Côté.)

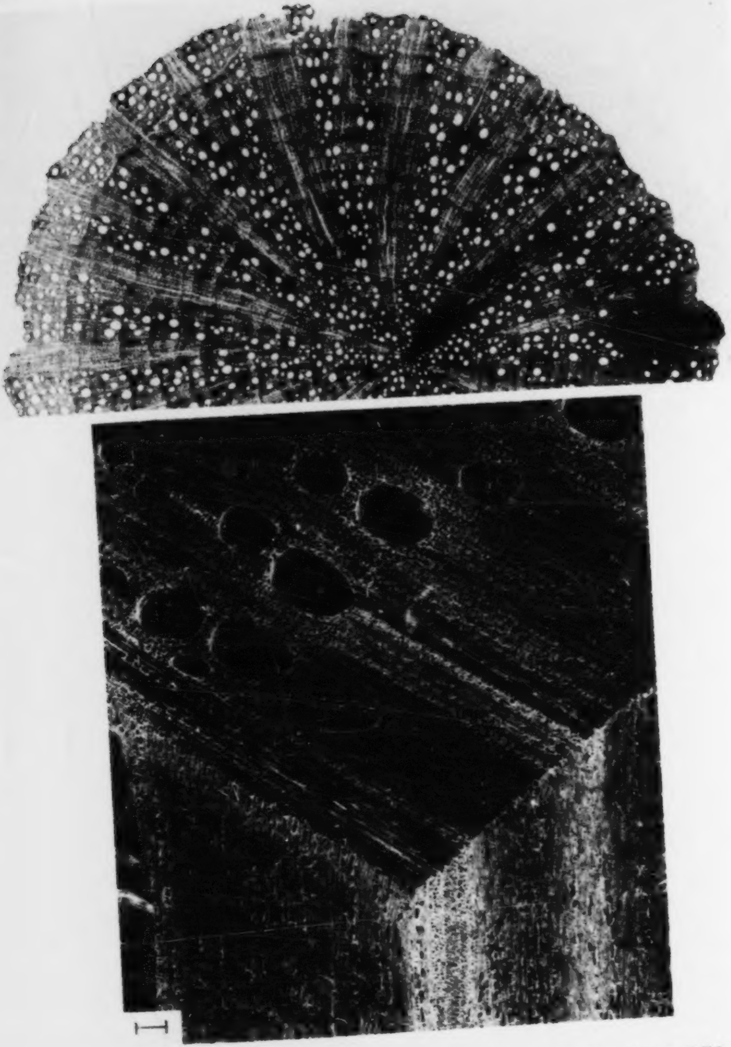

Figure 14-29.—Southern red oak rootwood. (Top) Transverse section of root 0.7 inch in diameter. (Bottom) Scanning electron micrograph of transverse section with radial section at left and tangential at right. Compare with southern red oak stemwood (fig. 5-39); no differences are apparent. Scale mark shows 100 micrometers. (Micrographs from files of W. A. Côté.)

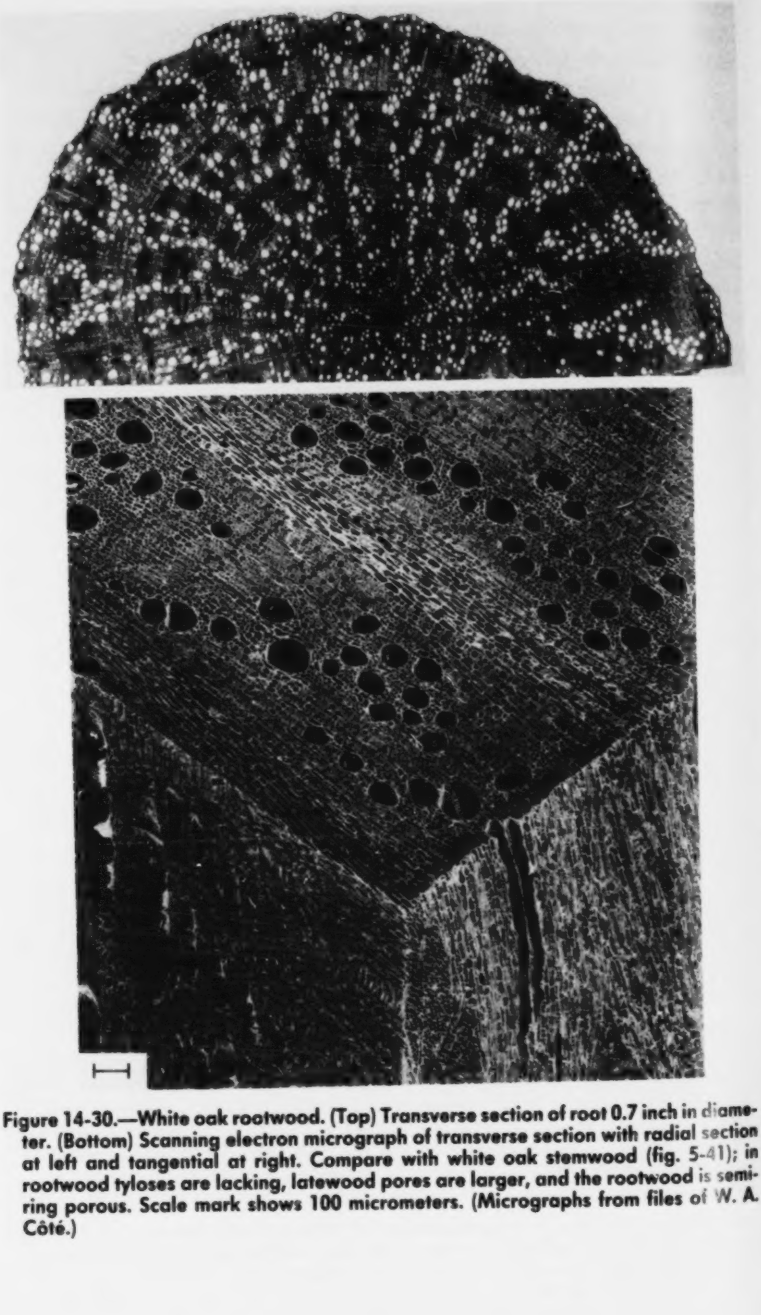

Figure 14-30.—White oak rootwood. (Top) Transverse section of root 0.7 inch in diameter. (Bottom) Scanning electron micrograph of transverse section with radial section at left and tangential at right. Compare with white oak stemwood (fig. 5-41); in rootwood tyloses are lacking, latewood pores are larger, and the rootwood is semi-ring porous. Scale mark shows 100 micrometers. (Micrographs from files of W. A. Côté.)

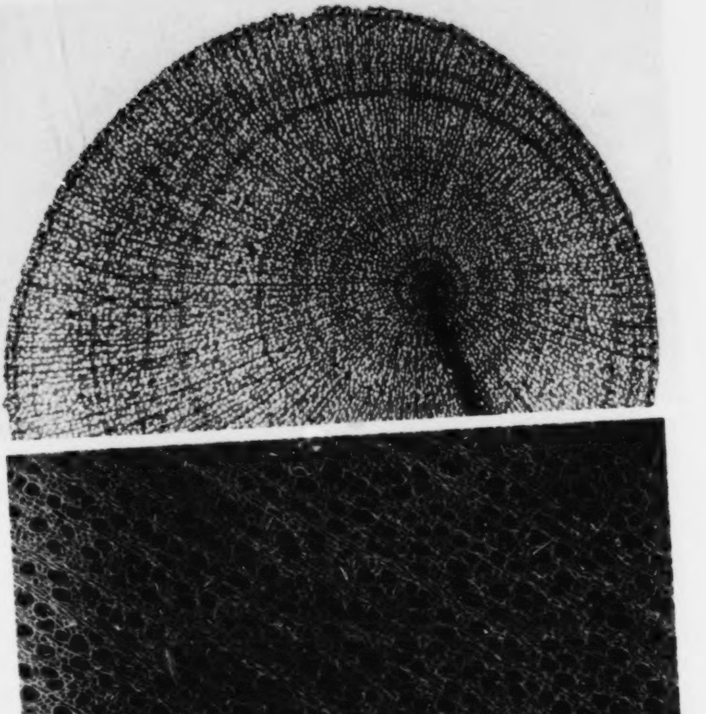

Figure 14-31.—Sweetgum rootwood. (Top) Transverse section of root 0.5 inch in diameter. (Bottom) Scanning electron micrograph of transverse section with radial section at left and tangential at right. Compare with sweetgum stemwood (fig. 5-43); rays are larger and pores (vessels) appear larger in diameter in rootwood. Scale mark shows 100 micrometers. (Micrographs from files of W. A. Côté.)

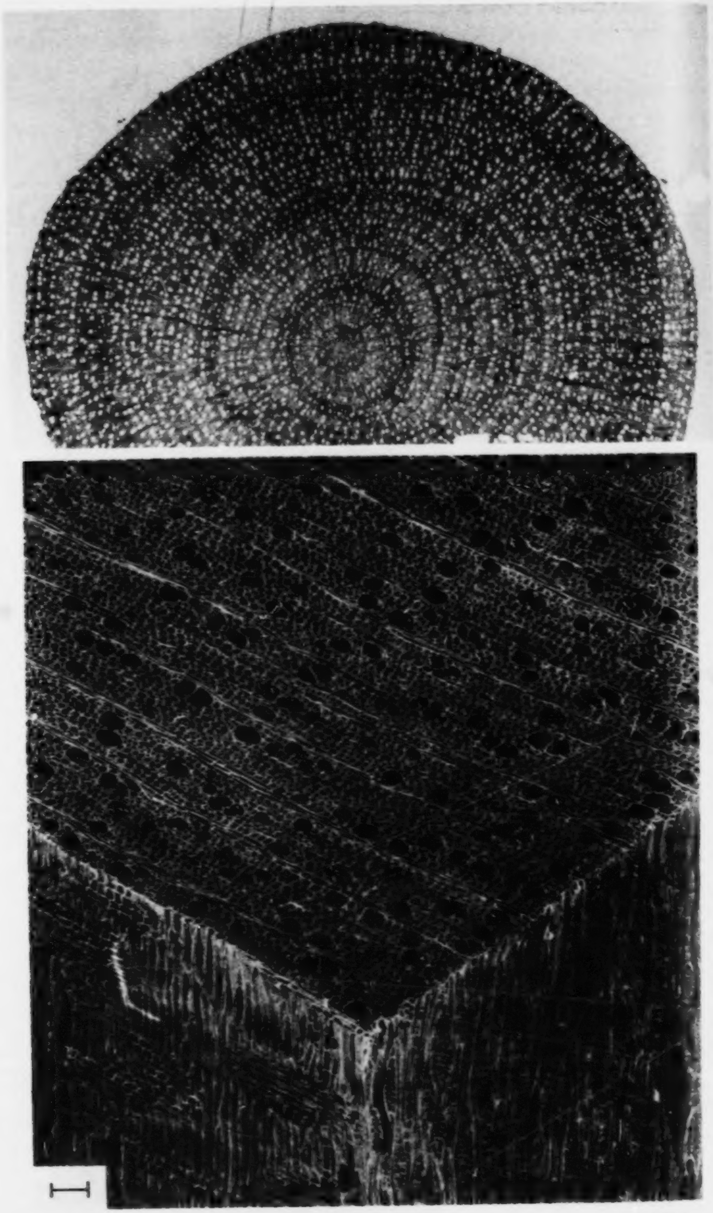

Figure 14-32.—Black tupelo rootwood. (Top) Transverse section of root 0.5 inch in diameter. (Bottom) Scanning electron micrograph of transverse section with radial section at left and tangential at right. Compare with black tupelo stemwood (fig. 5-44); rootwood pores (vessels) are not as numerous, rays are wider, and growth rings are not evident in rootwood. Scale mark shows 100 micrometers. (Micrographs from files of W. A. Côté.)

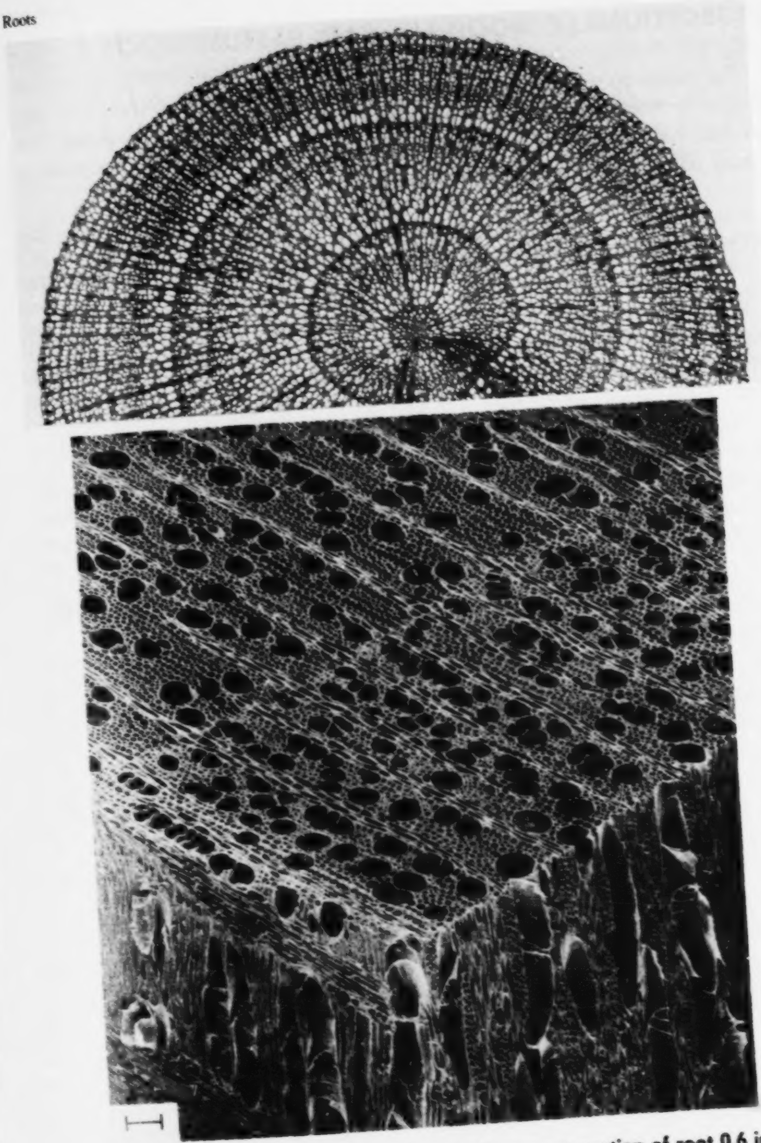

Figure 14-33.—Yellow-poplar rootwood. (Top) Transverse section of root 0.6 inch in diameter. (Bottom) Scanning electron micrograph of transverse section with radial section at left and tangential at right. Compare with yellow-poplar stemwood (fig. 5-45); pores do not appear to be as numerous in rootwood, but longer radial multiples are present, and rays are larger. Scale mark shows 100 micrometers. (Micrographs from files of W. A. Côté.)

PROPORTIONS OF WOOD AND BARK IN STUMP-ROOT

The stump-root systems (severed at 3-foot radius) of the 6-inch trees described by Koch and Manwiller[1] in table 14-2A had bark content averaging 12.6 percent, ranging from a low of 6.1 percent in black tupelo to 20.5 percent in scarlet oak (table 14-3), ovendry basis.

PROPORTIONS OF TISSUES IN WOOD OF STUMP-ROOT SYSTEM

In the Manwiller and Koch[1] study of 6-inch hardwoods, measurements of proportions of tissues were made on 15-degree wedges of wood sampled to statistically represent the stump-root system including lateral roots to a 3-foot radius. Each sample was sanded with four increasingly fine grades of sandpaper, the final being 600 grit. These finely sanded surfaces were sampled, in proportion to wood occurrence by volume, by use of a transparent grid and an integrating eyepiece on a microscope, and a dual-linear micrometer-microscope. Average tissue contents compared to those of stemwood and branchwood were as follows (from tables 5-3 and 14-4):

Tissue	Stump-root	Stemwood	Branchwood
		Percent of volume	
Vessels and vascular tracheids	17.9	20.5	19.7
Fibers	46.1	44.4	45.6
Rays	19.1	17.0	15.9
Parenchyma (other) and vascicentric tracheids	16.9	18.1	18.8
	100.0	100.0	100.0

TABLE 14-3.—*Proportions of wood and bark (ovendry-weight basis) in the central stump-root system of 6-inch trees of 22 species of hardwoods grown on southern pine sites* (Manwiller and Koch, see text footnote 1)[1,2]

Species	Stump-root wood		Stump-root bark	
	Lb	*Percent*	*Lb*	*Percent*
Ash, green	23.5	88.7	3.0	11.3
Ash, white	39.5	87.2	5.8	12.8
Elm, American	42.3	89.6	4.9	10.4
Elm, winged	48.0	91.8	4.3	8.2
Hackberry, sp.[3]	35.3	88.6	4.5	11.4
Hickory, sp.	42.4	84.8	7.6	15.2
Maple, red	54.6	87.2	8.0	12.8
Oak, black	37.9	81.6	8.5	18.4
Oak, blackjack	47.1	80.6	11.3	19.4
Oak, cherrybark	41.8	87.9	5.7	12.1
Oak, chestnut	45.2	87.7	6.4	12.3
Oak, laurel	44.4	92.0	3.9	8.0
Oak, northern red	48.2	84.0	9.2	16.0
Oak, post	49.0	90.4	5.2	9.6
Oak, scarlet	38.6	79.5	9.9	20.5
Oak, southern red	43.6	85.5	7.4	14.5
Oak, water	46.8	87.3	6.8	12.7
Oak, white	55.8	85.9	9.2	14.1
Sweetbay	40.8	90.0	4.5	10.0
Sweetgum	36.9	87.9	5.1	12.1
Tupelo, black	51.1	93.9	3.3	6.1
Yellow-poplar	26.0	90.4	2.8	9.6

[1] Roots severed at 3-foot radius.
[2] Each value is the average for three trees.
[3] Sugarberry.

TABLE 14-4.—*Proportions of tissues in wood from the stump-root system of 6-inch trees of 22 species of hardwood grown on southern pine sites.* (Manwiller and Koch, see text footnote 1)[1]

Species	Vessels and vascular tracheids		Fibers		Rays		Parenchyma and vasicentric tracheids	
	Percent							
Ash, green	14.9	(0.2)	54.4	(2.3)	15.2	(0.4)	15.4	(1.7)
Ash, white	16.0	(4.4)	57.0	(3.9)	13.0	(1.8)	13.7	(3.2)
Elm, American	23.2	(1.2)	44.1	(3.1)	13.3	(1.3)	19.2	(2.6)
Elm, winged	21.1	(1.8)	42.6	(2.5)	17.5	(1.0)	18.7	(.3)
Hackberry, sp.[2]	26.3	(3.6)	41.1	(2.0)	15.2	(.9)	17.2	(2.2)
Hickory, sp.	12.9	(1.9)	44.8	(.8)	24.8	(2.6)	18.9	(2.5)
Maple, red	12.0	(2.4)	60.3	(2.4)	17.6	(1.0)	9.9	(1.2)
Oak, black	13.9	(3.1)	42.5	(2.0)	24.0	(1.1)	19.4	(1.7)
Oak, blackjack	13.6	(2.0)	42.0	(1.1)	27.6	(3.7)	16.7	(1.4)
Oak, cherrybark	16.1	(.6)	41.1	(1.7)	20.2	(1.8)	22.5	(2.2)
Oak, chestnut	13.5	(.8)	45.0	(2.7)	20.6	(1.6)	20.7	(1.1)
Oak, laurel	18.3	(2.3)	40.5	(1.7)	20.7	(1.4)	20.4	(2.9)
Oak, northern red	11.3	(.7)	52.2	(5.6)	21.5	(1.7)	14.8	(6.2)
Oak, post	15.0	(2.4)	44.6	(2.4)	20.7	(1.6)	19.5	(3.1)
Oak, scarlet	13.5	(2.7)	41.3	(1.7)	25.7	(1.5)	19.3	(2.2)
Oak, southern red	14.0	(.8)	39.2	(2.3)	20.9	(2.4)	25.7	(3.8)
Oak, water	14.6	(2.8)	42.1	(3.0)	19.0	(1.5)	24.1	(1.3)
Oak, white	16.4	(.8)	42.4	(.9)	18.4	(.8)	22.7	(1.4)
Sweetbay	13.3	(1.9)	63.5	(.4)	15.8	(2.4)	7.2	(.8)
Sweetgum	39.9	(3.9)	33.7	(2.4)	16.0	(1.3)	10.2	(2.4)
Tupelo, black	19.2	(4.8)	57.4	(6.2)	15.0	(1.0)	8.2	(.7)
Yellow-poplar	35.0	(2.1)	41.8	(3.8)	16.0	(1.9)	7.1	(1.0)
Average	17.9		46.1		19.1		16.9	

[1] The first value given is the average for 3 trees; the second value, in parentheses, is the among-tree standard deviation.

[2] Sugarberry.

Fiber proportion is important to mill managers considering utilization of stump-root systems. Average proportion of fibers in wood of the stump-root systems was 46.1 percent; this compares to stemwood fiber proportion average of about 44.4 percent in these same species (table 5-3). In the stump-root systems, sweetbay and red maple had highest fiber content (63.5 and 60.3 percent). The two ashes and black tupelo had fiber contents from 54.4 to 57.4 percent. Northern red oak had 52.2 percent—the greatest fiber content of any of the 11 oaks sampled. The remaining 10 oaks, the elms, hackberry, and yellow-poplar had fiber proportions from 39.2 to 45.0 percent. Sweetgum had lowest fiber proportion (33.7 percent).

FIBER LENGTH AND TRANSVERSE DIMENSIONS IN WOOD AND BARK

As described earlier, in the Manwiller-Koch study[1] of 6-inch pine-site hardwoods a 2-inch-thick disk was removed at 1-foot intervals throughout each of 66 stump-root systems, including lateral roots within a 3-foot radius, for measurement of properties. For each property measured, a pith-centered wedge measuring 1/2-inch along the grain was removed from each disk and the wedges combined after the wood and bark were separated. This procedure sampled wood and bark in proportion to occurrence by volume, both within the disk and within the stump-root system. Fibers were prepared from both wood and bark specimens and lengths measured on an ampliscope. The macerated rootwood and bark fibers used for fiber length determinations were also measured for transverse dimensions using a microscope with 8X filar eyepiece. On each tree, 75 individual cell measurements were made on both bark and wood fibers of cell width, lumen diameters, and average wall thickness.

Wood fiber length.—Resulting data (tables 14-5, 5-4, and 5-7) indicate that in most species wood fibers in the stump-root system average about the same length, but are larger in diameter, than those from stemwood, as follows:

Statistic	Wood stump-root system	Stemwood	Branchwood
Fiber length, mm	1.27	1.27	0.96
Fiber radial diameter, µm	20.99	16.72	14.12
Tangential wall thickness, µm	5.32	4.44	3.71
Lumen radial diameter, µm	10.27	7.84	6.71

Longest wood fibers in the stump-root system were found in black tupelo, sweetgum, and yellow-poplar (1.90, 1.80, and 1.76 mm, respectively). Wood fibers of the stump-root system were shortest in red maple (0.79 mm). The remaining 18 species had wood fibers 1.00 to 1.40 mm long in the stump-root system.

TABLE 14-5.—*Wood fiber length and fiber transverse dimensions representative of stump-root systems of 6-inch hardwoods of 22 species sampled among southern pines* (Manwiller and Koch, see text footnote 1)[1]

Species	Fiber length	Fiber radial diameter	Tangential wall thickness	Lumen radial diameter
	mm	*µm*		
Ash, green	1.20 (0.04)	23.60 (1.38)	4.41 (0.32)	14.54 (1.13)
Ash, white	1.00 (.03)	21.31 (2.02)	4.10 (.23)	13.11 (2.40)
Elm, American	1.40 (.06)	15.90 (.21)	4.30 (.30)	7.31 (.80)
Elm, winged	1.30 (.06)	13.61 (.81)	4.95 (.47)	3.71 (.22)
Hackberry, sp.[2]	1.21 (.06)	14.39 (.72)	3.37 (.14)	7.66 (.43)
Hickory, sp.	1.17 (.12)	18.60 (.57)	4.60 (.64)	9.40 (1.14)
Maple, red	.79 (.02)	22.70 (.28)	4.22 (.28)	14.26 (.28)
Oak, black	1.10 (.09)	18.52 (1.21)	5.82 (.39)	6.89 (.50)
Oak, blackjack	1.01 (.08)	16.94 (.16)	5.34 (.21)	6.25 (.56)
Oak, cherrybark	1.28 (.06)	19.17 (1.00)	5.40 (.28)	8.37 (.53)
Oak, chestnut	1.09 (.04)	19.77 (1.97)	6.20 (.46)	7.38 (1.05)
Oak, laurel	1.26 (.06)	20.35 (.38)	5.86 (.13)	8.63 (.38)
Oak, northern red	1.15 (.13)	19.60 (.62)	5.75 (.15)	8.07 (.40)
Oak, post	1.10 (.15)	16.23 (.48)	5.46 (.33)	5.30 (.52)
Oak, scarlet	1.06 (.06)	19.08 (1.08)	5.73 (.22)	7.62 (.65)
Oak, southern red	1.28 (.08)	17.91 (.16)	5.59 (.17)	6.73 (.22)
Oak, water	1.37 (.06)	19.38 (1.88)	6.02 (.72)	7.32 (.50)
Oak, white	1.28 (.03)	17.37 (1.09)	5.57 (.57)	6.24 (.08)
Sweetbay	1.39 (.17)	33.77 (6.36)	5.00 (.06)	23.78 (6.42)
Sweetgum	1.80 (.08)	29.55 (1.33)	7.33 (1.18)	14.89 (1.02)
Tupelo, black	1.90 (.07)	35.14 (7.05)	6.25 (.26)	21.09 (8.07)
Yellow-poplar	1.76 (.05)	28.92 (1.44)	5.72 (.64)	17.49 (.35)
Average	1.27	20.99	5.32	10.27

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[1] The first value given is the average for 3 trees; the second value, in parentheses, is the among-tree standard deviation.

[2] Sugarberry.

TABLE 14-6.—*Bark fiber length and fiber transverse dimensions representative of stump-root systems of 6-inch hardwoods of 22 species sampled among southern pines* (Manwiller and Koch, see text footnote 1)[1]

Species	Fiber length	Fiber radial diameter	Tangential wall thickness	Lumen radial diameter
	mm	*µm*		
Ash, green	1.14 (0.29)	25.97 (2.00)	7.82 (3.22)	10.32 (8.37)
Ash, white	1.10 (.06)	21.77 (.91)	8.44 (.19)	4.89 (.74)
Elm, American	1.65 (.04)	12.18 (.59)	1.98 (.27)	8.21 (.04)
Elm, winged	1.33 (.11)	10.47 (1.22)	2.62 (.78)	5.23 (2.77)
Hackberry, sp.[2]	1.60 (.15)	12.42 (1.77)	2.23 (.59)	7.95 (2.95)
Hickory, sp.	1.60 (.15)	17.46 (.55)	2.63 (.26)	12.20 (.66)
Maple, red	.95 (.03)	19.37 (.34)	8.11 (.40)	3.15 (.63)
Oak, black	1.11 (.08)	20.78 (1.01)	8.57 (.92)	3.63 (.86)
Oak, blackjack	.96 (.01)	21.54 (.13)	9.17 (.30)	3.19 (.46)
Oak, cherrybark	1.13 (.06)	20.82 (.46)	8.91 (.48)	3.00 (.58)
Oak, chestnut	1.01 (.02)	20.25 (.87)	7.90 (1.36)	4.45 (2.70)
Oak, laurel	1.14 (.07)	20.83 (.49)	8.21 (.25)	4.40 (.70)
Oak, northern red	1.13 (.05)	19.79 (.57)	8.02 (.49)	3.75 (.62)
Oak, post	1.10 (.10)	18.07 (1.07)	7.95 (.44)	2.17 (.43)
Oak, scarlet	1.06 (.07)	21.34 (.32)	8.94 (.32)	3.45 (.48)
Oak, southern red	1.20 (.04)	21.17 (.52)	9.05 (.45)	3.07 (.46)
Oak, water	1.31 (.07)	20.94 (.56)	8.97 (.46)	3.00 (.56)
Oak, white	1.12 (.06)	20.29 (.94)	9.01 (.45)	2.26 (.08)
Sweetbay	1.14 (.05)	26.90 (2.02)	8.35 (.32)	10.20 (2.51)
Sweetgum	1.25 (.08)	26.59 (2.26)	11.29 (.72)	4.01 (2.86)
Tupelo, black	1.47 (.09)	29.97 (2.69)	13.70 (1.47)	2.41 (.23)
Yellow-poplar	1.42 (.04)	26.04 (.97)	9.63 (.93)	6.79 (1.88)
Average	1.22	20.68	7.80	5.08

[1] The first value given is the average for 3 trees; the second value, in parentheses, is the among-tree standard deviation.

[2] Sugarberry.

Wood fiber transverse dimensions.—Radial diameter of wood fibers in the stump-root systems varied greatly among species, as follows:

Species	Average radial diameter
	µm
Sweetbay and black tupelo	33.77 and 35.14
Ashes, red maple, laurel oak, sweetgum, and yellow-poplar	20.35 to 29.55
Hackberry, American elm, hickory, and all oaks except laurel oak	14.39 to 19.77
Winged elm	13.61

Tangential wall thickness averaged greatest in sweetgum (7.33 µm), and least in hackberry (3.37 µm); the remaining 20 species averaged between 4.10 and 6.25 µm. For comparison with stemwood and branchwood see table 5-7.

Bark fiber length.—Bark fibers in the stump-root system average longer, larger in diameter, and have about the same cell-wall thickness as fibers in stembark, as follows:

Statistic	Stembark (table 13-2)	Bark of stump-root system (table 14-6)
Fiber length, mm	0.98	1.22
Fiber radial diameter, µm	17.86	20.68
Tangential wall thickness, µm	7.69	7.80
Lumen radial diameter, µm	2.45	5.08

Longest fibers in bark of stump-root systems were found in American elm, hackberry, hickory, black tupelo, and yellow-poplar (1.65 to 1.42 mm); the shortest were in red maple and blackjack oak (0.95 and 0.96 mm, respectively). The remaining 15 species had bark fiber lengths from 1.01 to 1.33 mm (table 14-6.)

Bark fiber transverse dimensions.—Radial diameters of bark fibers in the stump-root systems were maximum in green ash, sweetbay, sweetgum, black tupelo, and yellow-poplar (25.97 to 29.97 µm); they were least in the elms and hackberry (10.47 to 12.42 µm). The remaining 14 species were intermediate, with bark fibers measuring 17.46 to 21.77 µm in radial diameter.

Tangential walls of bark fibers were thickest in sweetgum and black tupelo (11.29 and 13.70 µm); they were thinnest in the elms, hackberry, and hickory (1.98 to 2.63 µm). The remaining 16 species were intermediate with bark fiber tangential wall thicknesses from 7.82 to 9.63 µm.

14-5 MOISTURE CONTENT

In the 22 species of 6-inch pine-site hardwoods studied by Manwiller and Koch[1], moisture contents of the various tree portions averaged as follows (table 14-7):

Component	Moisture content (ovendry-weight basis)
	Percent
Stump-root system	88.8
Stem, including bark	74.8
Branches, including bark	74.0
Twigs	78.8
Foliage	139.0

Stump-root systems of sweetbay, sweetgum, and yellow-poplar exceeded 100 percent moisture content (table 14-7). Winged elm and white ash stump-root systems had lowest moisture content (56.8 and 68.6 percent). The remaining 17 species had stump-root moisture contents from 75.2 percent (hackberry) to 98.8 percent (black tupelo and green ash).

TABLE 14-7.—*Moisture content of components of 6-inch trees of 22 species of hardwoods sampled among southern pines* (Manwiller and Koch, see text footnote 1)[1]

Species	Stem: Wood and bark	Branches: Wood and bark	Twigs	Foliage	Wood and bark in central stump-root[2]
	Percent[3]				
Ash, green	57.5	68.0	79.6	185.5	98.8
Ash, white	47.3	55.3	59.4	113.8	68.6
Elm, American	86.0	77.1	85.2	190.5	76.7
Elm, winged	68.7	63.0	57.1	71.1	56.8
Hackberry, sp.[4]	66.4	63.1	57.2	80.8	75.2
Hickory, sp.	61.1	69.0	82.3	170.9	93.5
Maple, red	76.5	84.3	79.0	117.2	78.1
Oak, black	70.8	55.2	72.3	147.5	85.3
Oak, blackjack	72.0	58.0	42.9	108.1	88.9
Oak, cherrybark	62.4	62.4	80.6	89.0	88.6
Oak, chestnut	61.8	69.6	83.5	162.4	83.9
Oak, laurel	70.0	59.5	57.9	95.4	88.9
Oak, northern red	70.5	59.8	64.8	138.6	84.4
Oak, post	74.7	75.5	80.7	153.1	83.5
Oak, scarlet	74.9	72.2	73.2	135.0	93.4
Oak, southern red	75.9	68.0	76.2	113.8	92.9
Oak, water	68.7	75.9	64.7	98.4	87.6
Oak, white	70.1	67.4	111.8	121.5	85.4
Sweetbay	101.1	97.3	92.8	185.5	106.7
Sweetgum	115.8	97.1	114.5	192.0	123.8
Tupelo, black	89.7	123.8	105.0	181.3	98.8
Yellow-poplar	103.0	106.7	112.8	205.7	115.0

[1] Each value is the average for three trees.

[2] Moisture content was determined for the entire stump-root system to a 3-foot radius from the stem.

[3] Percent of ovendry weight.

[4] Sugarberry.

In a related, more extensive study (Manwiller 1975), moisture contents were determined for branch and stem wood and bark, separately and combined, for all but one (chestnut oak) of the 22 species described in table 14-7. In this larger study, data were collected from ten 6-inch trees of each species, distributed throughout that portion of the species range occurring in the South. Moisture content data for the more extensive study are summarized in table 8-2.

14-6 SPECIFIC GRAVITY

Manwiller and Koch[1] determined the specific gravity of wood and bark from the stump-root system of 22 pine-site 6-inch hardwoods from 45-degree wedges removed from disks proportionately sampled throughout each stump-root system to a 3-foot radius. The values (table 14-8) were based on ovendry weight and green volume, the latter determined by water immersion after saturation. An average wood (or bark) specific gravity for the stump-root system was obtained by adding the weights and volumes of the individual wedges of each tree to yield one ovendry weight and one green volume.

ROOTWOOD SPECIFIC GRAVITY

Wood of the stump-root systems of the 22 species described in table 14-8 averaged lower in specific gravity (0.513) than stemwood of the 22 species described by table 7-7 (0.572). Rootwood of winged elm had highest specific

TABLE 14-8.—*Specific gravity of wood and bark from the central stump-root systems (3-foot radius) of 6-inch trees of 22 species of hardwoods sampled among southern pines* (Manwiller and Koch, see text footnote 1)[1,2]

Species	Wood		Bark	
Ash, green	.421	(0.013)	.312	(0.019)
Ash, white	.492	(.034)	.369	(.023)
Elm, American	.533	(.010)	.383	(.016)
Elm, winged	.674	(.042)	.409	(.038)
Hackberry, sp.[3]	.453	(.004)	.551	(.079)
Hickory, sp.	.497	(.022)	.406	(.016)
Maple, red	.522	(.039)	.427	(.060)
Oak, black	.581	(.022)	.579	(.043)
Oak, blackjack	.525	(.026)	.527	(.050)
Oak, cherrybark	.562	(.029)	.441	(.037)
Oak, chestnut	.615	(.029)	.429	(.060)
Oak, laurel	.508	(.022)	.368	(.082)
Oak, northern red	.589	(.033)	.534	(.016)
Oak, post	.631	(.089)	.366	(.059)
Oak, scarlet	.549	(.051)	.473	(.144)
Oak, southern red	.539	(.015)	.511	(.005)
Oak, water	.529	(.037)	.404	(.051)
Oak, white	.596	(.036)	.369	(.051)
Sweetbay	.287	(.066)	.282	(.049)
Sweetgum	.391	(.016)	.389	(.027)
Tupelo, black	.423	(.059)	.255	(.025)
Yellow-poplar	.374	(.023)	.193	(.031)

[1] The first value given is the average for 3 trees; the second value, in parentheses, is the among-tree standard deviation.

[2] Based on green volume and ovendry weight.

[3] Sugarberry.

gravity (0.674) followed by post oak (0.631) and chestnut oak (0.615). Sweetbay rootwood had lowest specific gravity (0.287) with yellow-poplar (0.374) and sweetgum (0.391) slightly higher. The remaining 16 species had rootwood specific gravity in the range from 0.421 (green ash) to 0.596 (white oak).

ROOTBARK SPECIFIC GRAVITY

Bark of the stump-root systems of the 22 species described in table 14-8 averaged lower in specific gravity (0.408) than stembark of the 22 species described by table 7-7 (0.523). Rootbark specific gravity was highest in southern red oak, blackjack oak, northern red oak, hackberry, and black oak with range in these species-averages from 0.511 to 0.579. Yellow-poplar rootbark had lowest specific gravity (0.193) with black tupelo (0.255) and sweetbay (0.282) next lowest. The remaining 11 species had rootbark specific gravity in the range from 0.312 (green ash) to 0.473 (scarlet oak).

14-7 CHEMICAL CONSTITUENTS

From data available on other species, cellulose content in rootwood is probably slightly lower and lignin and extractives contents slightly higher than in stemwood (see tables 6-1, 6-14, 6-18, and 6-19 for data on above-ground tree components).

ASH CONTENT

Ash content in the stump-root systems of the 6-inch pine-site hardwoods of 22 species studied by Manwiller and Koch[1] averaged higher than in stems or branches of these species, as follows:

Tree component	Ash content (unextracted, ovendry-weight basis)
	Percent
Wood	
From stump-root system (table 14-9)	1.23
Stemwood (table 6-18)	.75
Branchwood (table 6-18)	.94
Bark	
From stump-root system (table 14-10)	9.93
Stembark (table 6-18)	7.87
Branchbark (table 6-18)	6.76

To make these ash determinations from the stump-root systems, rootwood was separated from bark of wedges and disks—which in aggregate statistically represented the stump-root system. Rootwood and root bark were ground (40 mesh) and analyzed separately by ashing them for 4 hours in a muffle furnace at 575°C. Specimens were not treated with nitric acid prior to ashing. Two replications of ash content determination were made for each of the three trees from each species, and values for the two replications averaged.

Rootwood of blackjack and post oaks had ash contents of 2.03 and 2.53 percent, while that of black tupelo and yellow-poplar had only 0.62 and 0.73 percent respectively. The other 18 species were intermediate (table 14-9).

Rootbark of hackberry had 16.42 percent ash—the highest percentage observed. Next were winged elm, hickory, post oak, and sweetbay—all of which had 12 to 13 percent. Lowest ash content (6.79 to 7.95 percent) was found in rootbark of chestnut, scarlet, southern red, and water oaks, and in white ash and yellow-poplar (table 14-10).

TABLE 14-9.—*Ash and mineral content of wood from the central stump-root system (to a 3-foot radius) of 6-inch trees of 22 species of hardwoods sampled among southern pines* (Manwiller and Koch, see text footnote 1)[1]

Species	Ash content[2]	Fe	Zn	Cu	Mn	Na	Mg	Ca	K	Al	P
	Percent	*Parts/million*									
Ash, green	1.09 (0.07)	404	21	89	9	54	476	1,575	2,087	2	151
Ash, white	.91 (.04)	121	6	64	1	35	626	1,234	1,763	1	313
Elm, American	1.57 (.41)	137	4	6	62	127	588	3,561	1,484	23	289
Elm, winged	.98 (.09)	91	4	10	27	49	270	1,971	1,500	16	323
Hackberry, sp.[3]	1.79 (.30)	192	9	18	29	288	1406	2,806	4,710	41	747
Hickory, sp.	1.36 (.27)	206	28	4	112	11	1712	1,587	2,971	73	170
Maple, red	1.41 (.92)	187	10	11	94	30	390	1,107	1,530	23	271
Oak, black	.89 (.17)	377	1	8	103	29	519	2,205	1,706	10	317
Oak, blackjack	2.03 (.70)	532	6	12	252	53	857	8,873	2,517	53	222
Oak, cherrybark	1.06 (.31)	1,043	2	3	314	103	317	1,781	1,444	2	236
Oak, chestnut	.83 (.51)	306	2	7	43	12	133	2,902	481	38	300
Oak, laurel	1.41 (.42)	1,453	6	14	244	53	382	2,277	2,244	38	186
Oak, northern red	1.28 (.23)	706	2	9	54	18	472	3,809	1,046	31	477
Oak, post	2.53 (.57)	1,608	3	9	68	22	388	7,843	1,064	8	216
Oak, scarlet	.93 (.37)	285	3	6	80	22	366	2,636	1,136	44	463
Oak, southern red	1.76 (.79)	827	2	9	114	36	689	1,704	1,549	12	158
Oak, water	.95 (.15)	69	6	13	129	51	333	1,863	1,602	46	241
Oak, white	.90 (.11)	1,274	3	10	77	9	173	1,814	1,266	40	183
Sweetbay	1.27 (.89)	195	7	15	120	133	317	887	1,748	10	465
Sweetgum	.82 (.05)	207	11	15	50	62	772	861	1,936	36	130
Tupelo-black	.62 (.12)	77	7	13	40	36	840	604	984	59	215
Yellow-poplar	.73 (.13)	118	9	16	35	35	373	1,104	1,834	10	198

[1] See footnote 1 of table 14-10 for method of mineral content determination.
[2] Ovendry-weight basis. The first value is the average for three trees; the second, in parentheses, is the among-tree variation.
[3] Sugarberry.

TABLE 14-10.—*Ash and mineral content of bark from central stump-root system (to a 3-foot radius) of 6-inch trees of 22 species of hardwoods sampled among southern pines* (Manwiller and Koch see text footnote 1)[1]

Species	Ash content[2]	Fe	Zn	Cu	Mn	Na	Mg	Ca	K	Al	P
	Percent	*Parts/million*									
Ash, green	10.37 (1.93)	143	17	71	69	72	1,997	34,817	3,002	219	258
Ash, white	7.40 (1.00)	254	13	79	44	60	1,229	24,508	2,956	447	369
Elm, American	11.67 (.58)	412	30	9	330	154	851	38,037	3,124	466	448
Elm, winged	12.30 (.31)	174	12	5	170	53	481	43,198	2,996	245	351
Hackberry sp.[3]	16.42 (1.11)	1,328	14	9	168	173	2,291	46,057	6,467	1,935	738
Hickory sp.	12.72 (2.89)	240	88	8	396	63	3,116	39,436	5,736	983	389
Maple, red	11.88 (1.04)	252	47	7	839	68	1,046	34,904	3,715	497	449
Oak, black	8.09 (2.03)	180	7	4	385	22	676	33,794	569	851	447
Oak, blackjack	9.38 (1.43)	311	6	5	548	42	633	31,517	1,130	708	196
Oak, cherrybark	9.24 (1.48)	443	6	4	1,380	89	405	31,612	2,370	597	393
Oak, chestnut	6.79 (1.96)	222	19	6	312	27	933	25,559	1,796	507	311
Oak, laurel	10.29 (1.74)	2,027	11	5	1,334	84	1,084	25,818	2,628	1,141	233
Oak, northern red	9.60 (2.87)	286	11	6	312	17	748	37,308	1,056	683	253

TABLE 14-10.—*Ash and mineral content of bark from central stump-root system (to a 3-foot radius) of 6-inch trees of 22 species of hardwoods sampled among southern pines* (Manwiller and Koch see text footnote 1)[1]—Continued

Species	Ash content[2]	Fe	Zn	Cu	Mn	Na	Mg	Ca	K	Al	P
	Percent	*Parts/million*									
Oak, post	12.01 (3.08)	236	10	6	130	76	1,762	41,153	4,467	429	287
Oak, scarlet	7.22 (1.64)	262	11	5	376	17	536	24,880	689	772	236
Oak, southern red	7.87 (1.34)	267	4	3	342	32	1,318	20,733	1,859	766	278
Oak, water	7.14 (1.60)	241	10	5	408	61	924	21,872	3,099	826	335
Oak, white	9.76 (1.23)	257	4	4	232	52	702	34,860	3,326	606	586
Sweetbay	12.97 (.68)	2,377	28	7	549	818	1,076	8,728	7,389	608	1,603
Sweetgum	9.12 (2.87)	223	24	9	312	130	1,997	25,565	3,016	774	230
Tupelo, black	8.20 (1.28)	381	11	4	243	69	2,543	19,155	4,783	1,184	420
Yellow-poplar	7.95 (1.38)	201	12	9	209	108	2,067	17,333	11,755	402	645

[1] Mineral contents of ashed specimens were determined (except for phosphorus) on a Perkin-Elmer Model 360 Atomic Absorption Spectrophotometer. Stock solutions were made for each element in accordance with the instrument manufacturer's instructions. Aliquots of the stock solutions were combined and diluted with deionized water to form the standards by which the instrument was calibrated. It was noted that the determination of sodium, magnesium, calcium, potassium, and manganese required the addition of a strontium ion (1,500 ppm solution of $SrCl_2$ in 0.3N HNO_3) in both samples and standards to mask the effect of various interferences. Therefore, two separate sets of standards were made: one with the strontium ion and one without. Likewise, two blank standards of 0.3N HNO_3 were made for zeroing the instrument: one with and the other without the strontium addition. Zinc, copper, and iron did not require the addition of strontium, and could be tested without dilution except in cases where high concentrations of an element required dilution in order to bring it within the range of the standards. Phosphorus content was measured on a Perkin-Elmer UV-VIS spectrophotometer by the ascorbic acid method (John 1970).

[2] Ovendry weight basis. The first value is the average for three trees; the second value, in parentheses, is the among-tree variation.

[3] Sugarberry.

MINERAL CONTENT

Mineral contents in bark and wood of the stump-root systems of the species sampled by Manwiller and Koch[1] averaged as follows (tables 14-9 and 14-10):

Element	Bark	Wood
	Parts/Million	
Fe	487	473
Zn	18	7
Cu	12	16
Mn	413	94
Na	104	58
Mg	1,292	564
Ca	30,038	2,500
K	3,542	1,755
Al	711	28
P	430	285

Variations in mineral contents among the species were significant. Following are species whose stump-root wood and bark averaged most and least of each mineral (from tables 14-9 and 14-10):

Tissue and mineral	Range
	Parts/Million
Wood	
Fe	Post oak (1,608); water oak (69)
Zn	Hickory (28); black oak (1)
Cu	Green ash (89); cherrybark oak (3)
Mn	Cherrybark oak (314); white ash (1)
Na	Hackberry (288); white oak (9)
Mg	Hickory (1,712); chestnut oak (133)
Ca	Blackjack oak (8,873); black tupelo (604)
K	Hackberry (4,710); chestnut oak (481)
Al	Hickory (73); white ash (1)
P	Hackberry (747); sweetgum (130)
Bark	
Fe	Sweetbay (2,377); green ash (143)
Zn	Hickory (88); southern red oak and white oak (4)
Cu	White ash (79); southern red oak (3)
Mn	Cherrybark oak (1,380); white ash (44)
Na	Sweetbay (818); northern red oak and scarlet oak (17)
Mg	Hickory (3,116); cherrybark oak (405)
Ca	Hackberry (46,057); sweetbay (8,728)
K	Yellow-poplar (11,755); black oak (569)
Al	Hackberry (1,935); green ash (219)
P	Sweetbay (1,603); blackjack oak (196)

STARCH CONTENT

Wargo (1975) noted that radial growth of stems indicates how vigorous a tree has been, but does not necessarily indicate current vigor. Starch content of roots, however, may be a good index of current tree vigor. In most deciduous trees starch is stored in high concentrations in roots when photosynthetic capacity is high, but is diminished by stresses such as defoliation, drought, and air pollution.

Wargo (1975) devised a visual technique of determining starch content, based on iodine-staining of starch granules. By chemical analysis (Wargo 1976) he found that the variation of starch content among roots of a tree was small if root samples were of a single diameter class. In his study of five northern red oaks and five white oaks, he found that starch content varied inversely with root diameter because as root diameter decreases, the proportion of ray tissue to woody tissue increases, resulting in a corresponding increase in starch content. It follows that starch content in roots increases with increased distance from the root collar (table 14-11). Roots of northern red oaks had greater starch content than those of white oaks in these trees sampled in December in New England.

TABLE 14-11.—*Starch content (by chemical analysis) in roots of five white and five northern red oaks related to distance from root collar and to visual rating of starch content after iodine straining* (Wargo 1976)

Species and visual rating of starch content	Distance from root collar, meters			
	0.00	0.45	1.05	1.65
	Percent of dry weight			
White oak				
High	5	6	11	11
Medium	4	4	8	8
Medium	3	5	7	9
Low	1	2	5	7
Depleted	0	.3	0	0
Northern red oak				
High	11	16	27	24
High	6	11	14	18
High	6	12	21	22
High	6	10	16	19
Medium	8	9	14	15

14-8 HEAT OF COMBUSTION

Heat of combustion of the wood and bark of stump-root systems of the 6-inch pine-site hardwoods of 22 species studied by Manwiller and Koch[1] averaged higher than for stemwood and stembark as follows (table 14-12):

Tree component	Higher heat of combustion (higher heating value)
	Btu/ovendry pound
Wood	
From stump-root system (table 14-12)	8,333
Stemwood (table 9-12)	7,827
Branchwood (table 9-12)	7,784
Bark	
From stump-root system (table 14-12)	7,657
Stembark (table 9-12)	7,593
Branchbark (table 9-12)	7,632

TABLE 14-12.—*Heat of combustion of wood and bark from the stump-root system (to a 3-foot radius) of 6-inch hardwood trees of 22 species sampled from among southern pines* (Manwiller and Koch, see text footnote 1)[1] [2]

Species	Rootwood	Rootbark
	-----*Btu/ovendry pound*-----	
Ash, green	8,318	7,416
Ash, white	8,249	7,763
Elm, American	8,242	7,173
Elm, winged	8,282	7,231
Hackberry[3]	9,038	6,997
Hickory	8,267	7,400
Maple, red	8,410	7,418
Oak, black	8,179	7,868
Oak, blackjack	8,303	7,967
Oak, cherrybark	8,095	7,578
Oak, chestnut	8,122	7,976
Oak, laurel	8,453	8,021
Oak, northern red	7,972	7,682
Oak, post	8,879	7,290
Oak, scarlet	8,140	8,021
Oak, southern red	8,289	8,273
Oak, water	8,728	7,593
Oak, white	8,091	7,270
Sweetbay	8,242	7,942
Sweetgum	8,172	7,688
Tupelo, black	8,111	7,807
Yellow-poplar	8,735	7,776
Average	8,333	7,657

[1] Each value is the average for three trees.

[2] Higher heating value determined in an oxygen bomb calorimeter; unextracted wood and bark.

[3] Sugarberry.

Rootwood averaged higher in heat of combustion than rootbark, probably because it contains significantly less ash. Hackberry rootwood had highest heat of combustion (9,038 Btu/lb); post oak (8,879), yellow-poplar (8,735), and water oak (8,728) were next highest. Northern red oak rootwood, at 7,972 Btu/lb, had lowest heat of combustion. Rootwood of the other 17 species had heats of combustion from 8,091 to 8,453 Btu/lb.

While hackberry rootwood had the highest heat of combustion, its rootbark had lowest (6,997 Btu/lb), probably because of its 16.42 percent ash content. Southern red oak rootbark, with only 7.87 percent ash content, had highest heat of combustion (8,273 Btu/lb). Rootbark of the other 20 species had values from 7,173 to 8,021 Btu/lb.

14-9 UTILIZATION

From the data in figures 14-4 through 14-26 it is seen that the stump-root systems of 6-inch pine-site hardwoods, if trimmed to 1-foot radius, averaged about 24.4 percent of the weight of stems with bark, and have average weight of about 34 pounds, ovendry basis (table 14-28). About 100 such small stump-root systems, with laterals severed at 1-foot radius, would be roughly equivalent in ovendry weight to a cord of hardwood pulp.

HARVESTING

With the proper equipment, it would seem most efficient to extract and bunch trees with central root masses attached to stems, rather than harvest stump-root systems in a secondary operation. The carrot-like form of southern pine root systems (Koch 1972, p. 545, 553, 554, 559) permitted development of commercial equipment to efficiently pull and bunch southern pine trees with central root mass attached (Koch 1976). Experiments with pine site hardwoods (section 16-7 and figures 16-32 and 16-33) indicate that it is also possible to pull and bunch small hardwoods, but their branched root form (figs. 14-5 through 14-26) makes them more difficult to pull with this equipment than the southern pines.

It is also possible to harvest hardwood stumps after upper tree portions have been removed. The vibratory stump puller shown in figure 16-31 has promise, but reduction of the resulting assembage of lateral roots is difficult. Both the Pallari stump harvester (fig. 16-28) and the OSA harvester (fig. 16-29) simultaneously extract and split stump-root systems into manageable portions preparatory to forwarding and transport to mill (fig. 16-30).

In Mackmyra, Sweden, an efficient beneficiation plant is in commercial operation to prepare rootwood for pulping (fig. 17-16). In the United States, one operation is also successfully pulping rootwood (Davis and Hurley 1978).

USE FOR PULP

Stump-root systems compare with stemwood of small pine-site hardwoods about as follows (average, not weighted by volume, of 22 species):

Characteristic	Stump-root wood	Stemwood
Moisture content, percent	88.8	74.8
Specific gravity, O.D. weight and green volume	0.513	0.572
Ash content, percent	1.23	0.75
Lignin, percent	—	24
Cellulose, percent	—	40
Fiber proportion, percent volumetric	46	44
Fiber length, mm	1.27	1.27
Fiber radial diameter, µm	20.99	16.72
Fiber tangential wall thickness, µm	10.27	4.44

It would be possible to introduce a significant proportion of suitably cleaned hardwood stumpwood into digesters pulping stemwood of southern hardwoods, but this development seems unlikely as long as hardwood stemwood of these species is in excess supply. Readers needing additional information on the pulping of stump-root systems are referred to Hyland (1974, p. 53), Peckham and McKee (1975), Hartler (1976), Palenius (1976), Anonymous (1977), Blomqvist (1978), Davis and Hurley (1978), and Viklund (1978).

USE FOR FLAKEBOARD

Howard (1974) and Biblis and Lee (1978) made flakeboards from the central root mass of slash pine and loblolly pine. It does not seem likely, however, that stump-root systems of pine-site hardwoods will be utilized for this purpose as long as stemwood remains in surplus supply.

USE FOR ENERGY

Wood and bark from stump-root systems of small pine-site hardwoods have higher heat of combustion than wood and bark from their stems, but also have higher moisture content and ash content, as follows (see table 8-2 for moisture content of above-ground wood and bark):

Material	Heat of combustion (higher heating value)	Moisture content	Ash content
	Btu/ovendry pound	---*Percent of dry weight*---	
Wood			
Wood from stump-root	8,333	88.8 (with bark)	1.23
Stemwood	7,827	73.5	.75
Bark			
Bark from stump-root	7,657	88.8 (with wood)	9.93
Stembark	7,593	67.6	7.87

It seems possible that stump-root systems of pine-site hardwoods pulled with stems during harvest, or in a secondary operation during site preparation or land clearing, could find use as fuel or energy feed stock. Large-scale land clearing during removal of overburden from Midsouth lignite fields presents an opportunity for such use, as does site preparation for intensive forestry or agriculture.

14-10 LITERATURE CITED

Anonymous. 1977. Finnish mill makes printing papers with 20% stumpwood. Tappi 60(9):32.

Biblis, E. J., W. C. Lee. 1978. Properties of particleboard from loblolly pine rootwood and aboveground stumpwood. For. Prod. J. 28(11):55-56.

Blomqvist, L. 1978. An industrial plant for chipping stump and rootwood for chemical pulping. *In* Complete tree utilization of southern pine: symp. proc., New Orleans, La., April 17-19. C. W. McMillin, Ed. For. Prod. Res. Soc., Madison, Wis., p. 294-298.

Carpenter, I. W. and A. T. Guard. 1954. Anatomy and morphology of the seedling roots of four species of the genus *Quercus*. J. of For. 52:269-274.

Chittenden, A. K. and W. K. Hatt. 1905. The red gum. The mechanical properties of red gum wood. U.S. Dep. Agric., Bur. of For., Bull. No. 58. 56 p. Washington, D.C.

Cutler, D. F. 1976. Variation in root wood anatomy. Leiden Bot. Ser. 3:143-156.

Davis, B. M., and D. W. Hurley. 1978. Fiber from a southern pine stump-root system? *In* Complete tree utilization of southern pine: Symp. Proc., New Orleans, La., C. W. McMillin, ed. For. Prod. Res. Soc., Madison, Wis., p. 274-276.

Esau, K. 1977. The root: Secondary state of growth and adventitious roots. Ch. 15 *in* Anatomy of seed plants. 2nd ed. John Wiley and Sons, New York. p. 243-256.

Francis, J. K. 1979. Yellow-poplar rooting habits. U.S. Dep. Agric., For. Serv. Res. Note S0-246. 3 p.

Grano, C. X. 1970. Eradicating understory hardwoods by repeated prescribed burning. U.S. Dep. Agric., For. Serv., Res. Pap. SO-56. 11 p.

Guilkey, P. C. 1957. Silvical characteristics of American elm (*Ulmus americana*). U.S. Dep. Agric., For. Serv., Stn. Pap. No. 54. 19 p. Lake States For. Exp. Stn.

Harris, W. F., R. A. Goldstein, and G. S. Henderson. 1973. Analysis of forest biomass pools, annual primary production and turnover of biomass for a mixed deciduous forest watershed. *In* IUFRO Biomass Studies, H. E. Young, ed. Univ. Main, Orono. P. 43-64.

Hartler, N. 1976. Stump and root wood for pulping. Appl. Polym. Symp. No. 28:517-527. San Francisco, Ca.: John Wiley & Sons, Inc.

Hollis, E. L., Jr. 1966. The effect of cultural treatments on root development of hardwood seedlings. M. F. thesis. La. State Univ., Baton Rouge. 73 p.

Hook, D. D. and C. L. Brown. 1973. Root adaptations and relative flood tolerance of five hardwood species. For. Sci. 19:225-229.

Howard, E. T. 1974. Slash pine rootwood in flakeboard. For. Prod. J. 24(6):25-35.

Hyland, F. 1974. Fiber analysis and distribution in the leaves, juvenile stems and roots of ten Maine trees and shrubs. Life Sci. Agric. Exp. Stn. Tech. Bull. 71, 67 p. Univ. of Maine, Orono, Maine.

John, M. K. 1970. Colorimetric determination of phosphorus in soil and plant material with ascorbic acid. Soil Sci. 109:214-220.

Johnson, F. L. and P. G. Risser. 1974. Biomass, annual net primary production, and dynamics of six mineral elements in a post oak-blackjack oak forest. Ecol. 55:1246-1258.

Koch, P. 1972. Utilization of the southern pines. U.S. Dep. Agric., For. Serv., Agric. Handb. 420. 1663 p. 2 vol. U.S. Govt. Print. Off., Washington, D.C.

Koch, P. 1976. New technique for harvesting southern pines with taproot attached can extend pulpwood resources significantly. Appl. Polym. Symp. 28:403-420.

Kochenderfer, J. N. 1973. Root distribution under some forest types native to West Virginia. Ecol. 54(2):445-448.

Lyford, W. H. 1980. Development of the root system of northern red oak (*Quercus rubra* L.). Harvard For. Pap. No. 21. Harvard For., Harvard Univ., Petersham, Mass. 30 p.

Manwiller, F. G. 1975. Wood and bark moisture contents of small-diameter hardwoods growing on southern pine sites. Wood Sci. 8:384-388.

Palenius, I. 1976. The state of whole-tree utilization in Scandinavia. Tappi 59(7):72-74.

Peckham, J. R. and R. C. McKee. 1975. Using stumpwood to meet future fiber needs—practical aspects. Pulp & Pap. 49(14):53-55.

Robbins, W. W., T. E. Weir, and C. R. Stocking. 1964. Botany—An introduction to plant science. 3rd ed. John Wiley and Sons, New York. 614 p.

Sirois, D. L. 1977. Feasibility of harvesting southern hardwood trees by extraction. Amer. Soc. Agric. Eng. Pap. 77-1567, 16 p.

Smith, P., and L. Every. 1980. Rooting habits of selected commercial tree species of the eastern United States—A bibliography. Bibliographies and Literature of Agric. No. 10. U.S. Dep. Agric., For. Serv. 59 p.

Stout, B. F. 1968. Root systems of deciduous trees. Amer. Nurseryman 127(1):13, 120-122.

Torrey, J. G. and L. J. Feldman. 1977. The organization and function of the root apex. Am. Sci. 65(3):334-344.

Viklund, G. 1978. Cleaning raw material better in the forest must really reckon with stumpwood chips. Svensk Papperstidning 81(13):421-433.

Wargo, P. M. 1975. Estimating starch content in roots of deciduous trees—a visual technique. U.S. Dep. Agric., For. Serv., Res. Pap. NE-313. 9 p.

Wargo, P. M. 1976. Variation of starch content among and within roots of red and white oak trees. For. Sci. 22(4):468-471.

Wilson, B. F. 1964. Structure and growth of woody roots of *Acer rubrum* L. Harvard For. Pap. No. 11, 14 p. Petersham, Mass.: Harvard Univ.

Wright, J. W. 1959. Silvical characteristics of green ash (*Fraxinus pennsylvanica*). U.S. Dep. Agric., For. Serv., Stn. Pap. 126. 18 p. Northeast. For. Exp. Stn., Upper Darby, Pa.

Young, H. E., C. B. Gammon, and L. E. Hoar. 1963. Potential fiber from red spruce and red maple logging residues. Tappi 46:256-259.

15

Foliage and Seeds

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CHAPTER 15

Foliage and Seeds

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CHAPTER 15

Foliage and Seeds

Many studies have explored the role of leaves in tree growth. Another sizeable body of literature is concerned with the effectiveness of foliar fertilizers in accelerating growth of desired trees, and the effectiveness of foliar herbicides in killing unwanted trees. But utilization of the foliage of pine-site hardwoods has not been intensively studied, and data on its usage are meager except as they relate to deer browse.

Literature on the utilization of seeds from pine-site hardwoods is largely concerned with the consumption of acorns and hickory nuts by quail, grouse, turkey, squirrels, and deer.

Industrial utilization of foliage and seeds (see chapter 16 for discussion of procedures in harvesting trees complete with foliage) removes significant amounts of nutrients from the forest, in contrast to use as forage by wildlife, where recycling occurs. Most of the industrial systems that capture foliage—e.g., whole-tree chipping—leave litter intact on the forest floor. Because existing pine-site hardwoods average about 40 years of age by the time they measure 6 inches in dbh, tonnage of fallen leaves and litter is many times greater than that on trees at time of harvest.

Many silviculturists believe that in southern forests managed for pulpwood or sawtimber, fresh foliage can be harvested along with tree bole and crown, but that litter on the forest floor should not be destroyed. Some widely used site preparation procedures—e.g., shear, windrow, and burn—incinerate litter as well as green leaves with resultant loss of most of the nitrogen and some of the phosphorus in the material burned. Proponents of short-rotation hardwood plantations grown for fuel usually visualize whole-tree harvest only in winter months after the leaves have dropped. Such systematic short-rotation harvest would call for simultaneous assessment of the need for fertilization, especially if green foliage were removed with each rotation. Readers interested in a summary of the effects of utilization on nutrient regimes will find Switzer et al. (1978) and Tippin (1978) useful.

15-1 FOLIAGE FORMATION AND ANATOMY[1]

As noted in chapter 4, water from tree roots is conducted upward in the outer portion of the woody stem by tensions created through transpiration in the leaves and is distributed to cambial and other living cells by osmotic forces. Food mainly in the form of sugars, photosynthesized in the leaves from carbon dioxide and water, is transported through the living inner bark to the cambium and to the horizontal rays; oxygen, another photosynthetic product, is liberated to the atmosphere.

LEAF ORIGIN AND EXTERNAL FORM

Leaves are borne on stems; attachment points are termed **nodes**. The upper angle between a leaf and the stem to which it is attached is the **axil** (fig. 15-1). Leaves maintain their shape through support of an internal structural framework of **veins**.

Leaves of pine-site hardwoods arise from meristematic tissue on buds that contain the undeveloped growing points of stems. Certain cells in the outermost layers of the growing point divide to form outgrowths termed **leaf primordia**. Leaves in pine-site hardwoods develop in the bud from these primordia—first by **apical growth** at the tips, and later by **intercalary growth** not restricted to the apex. When a few millimeters long, leaves continue to grow by enlarging throughout their area (visualize the surface-expansion of an inflating balloon) until the leaf reaches mature size, and growth ceases.

Leaf parts and arrangment.—Leaves of pine-site hardwoods are comprised of the **blade**, and the leafstalk or **petiole** by which the blade is attached to the stem or twig. About half the species (elms, hackberry, sweetbay, sweetgum, yellow-poplar, and some of the oaks) have two small appendages at the base of the petiole termed **stipules** (fig. 15-1). The gross structure of foliage of pine-site hardwoods is illustrated in figures 3-33 through 3-58, and their foliage is keyed in section 3-2. Of the 22 species and species groups listed in table 3-1, all but three have **simple leaves**. The exceptions include the true hickories which have **alternately arranged odd-pinnately compound leaves** with blades divided into leaflets (figs. 3-37 through 3-40); green ash and white ash also have odd-pinnately compound leaves, but they have **opposite arrangement** (figs. 3-33 and 3-34).

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[1] Bold-face terms in this section not otherwise defined, are defined in table 3-2.

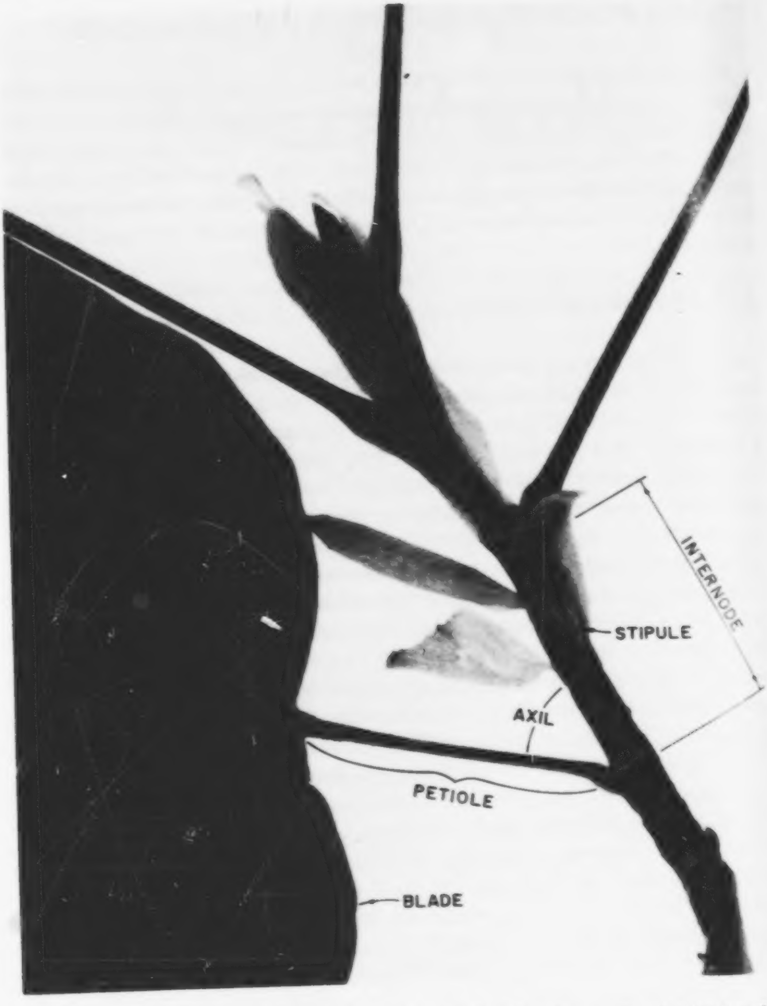
INTERNODE
STIPULE
AXIL
PETIOLE
BLADE

Figure 15-1.—Portion of a branch of yellow-poplar showing parts of a leaf and its attachment to the stem.

Venation.—Leaf blades are strengthened and stiffened by veins made up chiefly of conducting (vascular) tissue continuous with that of the petiole and stem. Veins distribute water and dissolved inorganic salts throughout the leaf blades and carry away elaborated foods. Pine-site hardwoods have leaves with **netted venation**, that is, the veins branch repeatedly forming a network throughout the blade (fig. 15-2). Twenty of the 22 species or species groups listed in table 3-1 have a principal central vein, called the **midrib** from which other veins branch; this pattern is termed **pinnate venation**. In sweetgum and red maple, several large veins of approximately equal size arise at a common point at the top of the petiole and spread out fan-like through the blade to form **palmate venation** (fig. 15-2).

LEAF ANATOMY[2]

Leaves of pine-site hardwoods viewed in transverse section (fig. 15-3) show three groups of tissues: **epidermis, mesophyll,** and **veins** specialized respectively for evaporation control, food elaboration, and conduction of liquids.

Epidermis.—The epidermis, a single layer of cells forming a surface skin, covers the entire leaf area on top and bottom. It protects internal tissues of leaves from excessive loss of moisture. Outer walls of epidermal cells are frequently thickened and are usually covered with a layer of **cutin,** a waxy material secreted by the protoplasts of the epidermal cells. Epidermal cells are generally colorless, although in some species pigments may be dissolved in cell sap, e.g., in black tupelo, purple or blackish coloration may appear from midsummer on to leaf fall.

Certain epidermal cells, chiefly on the lower surfaces of leaves, contain **chloroplasts** (chlorophyll-bearing bodies found outside of cell nuclei). These **guard cells** are somewhat bean-shaped as seen in surface view, and are arranged in pairs more or less regularly distributed among the more numerous, colorless cells of the epidermis (fig. 15-4 and 15-5). Each pair of guard cells encloses a small pore or stoma (figs. 15-3 and 15-5), permitting water evaporation and gaseous exchange between the inside of the leaf and the external atmosphere. As these paired guard cells expand and contract with changes in their water content, the size of the stoma varies. When the guard cells are expanded, the stomata are open; when they contract, the stomata are nearly or completely closed.

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[2] Text under this heading is condensed from Fuller and Tippo (1949) with addition of U.S. Forest Service illustrations and some data from the literature specific to pine-site hardwoods.

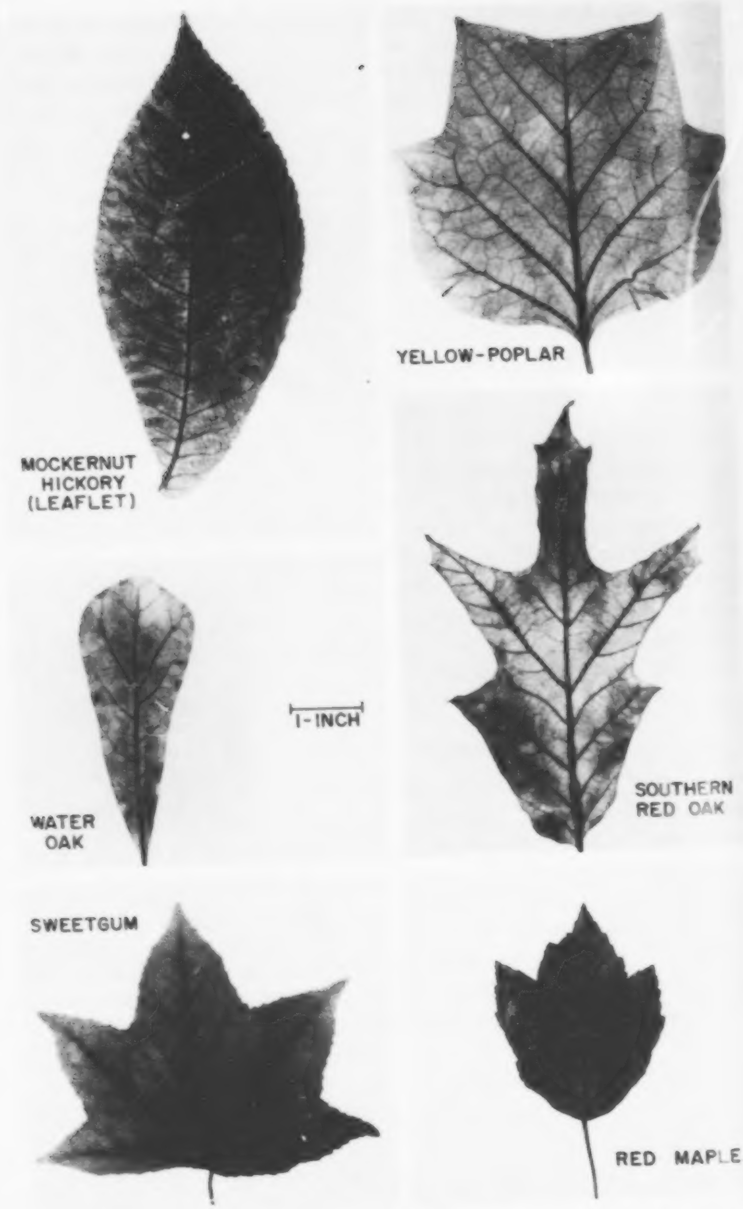
MOCKERNUT
HICKORY
(LEAFLET)
YELLOW-POPLAR
WATER
OAK
1-INCH
SOUTHERN
RED OAK
SWEETGUM
RED MAPLE

Figure 15-2.—Variations in netted venation pattern in leaves of pine-site hardwoods. (Top and center) Pinnate venation with midrib. (Bottom) Palmate venation.

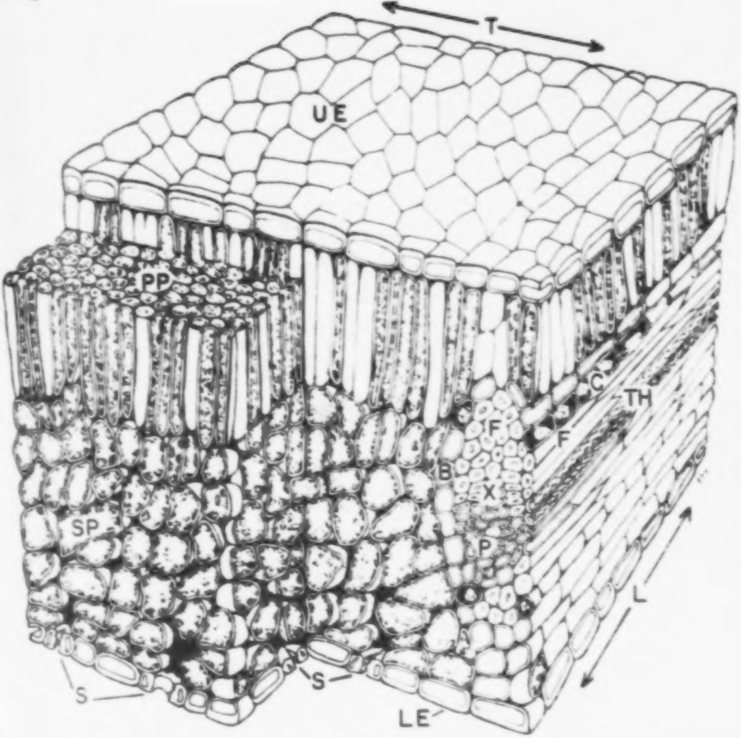

Figure 15-3.—Section of a typical white oak leaf showing both transverse (T) and longitudinal (L) aspects. A bundle-sheath (B) encloses the vascular bundle which contains phloem (P), xylem (X), and fibers (F). Some xylem elements are shown to contain spiral thickenings (TH). Also associated with the bundle-sheath are cells which contain crystals (C). The palisade (PP) and spongy (SP) parenchyma both contain chloroplasts. Other labeled areas are: upper epidermis (UE), lower epidermis (LE), and stomata (S). The cube depicted represents an average and measures about 250 micrometers on each side; the scale varies according to leaf position in the tree. (Drawing constructed by E. T. Howard and M. Folsom.)

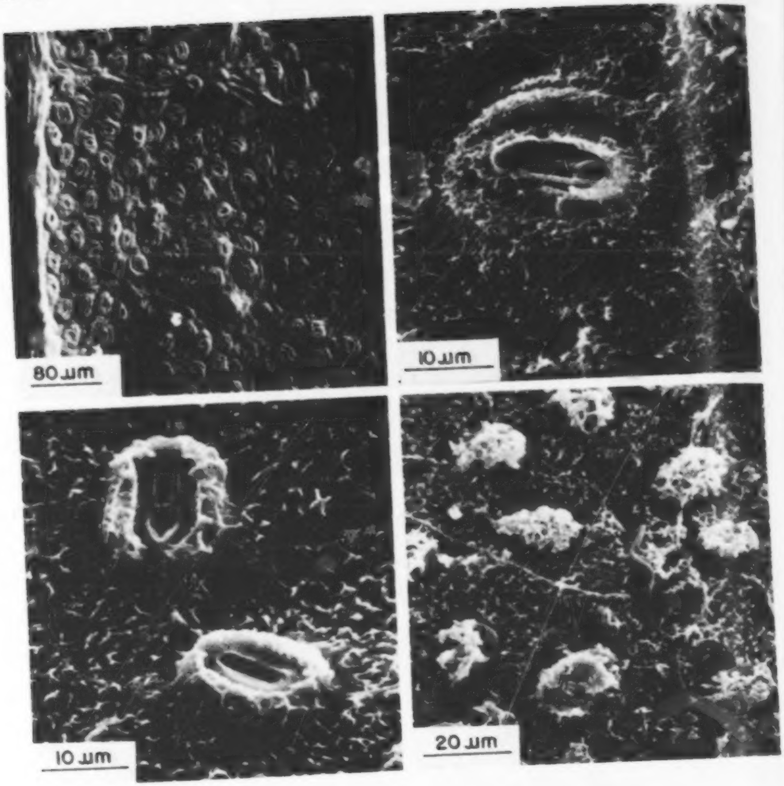

Figure 15-4.—Scanning electron micgrographs of stomata in lower surfaces of leaves of three oaks. (Top left) Small stomata dot surface of northern red oak leaf; vein structure visible at left and top of image. (Top right) Northern red oak stoma at higher magnification. (Bottom left) Encrustation surrounds but does not cover, stomata in chestnut oak leaf. (Bottom right) Encrustation appears to obstruct stomata in white oak leaf. (Photos from files of C. W. McMillin, U.S. Dep. Agric. For. Serv.)

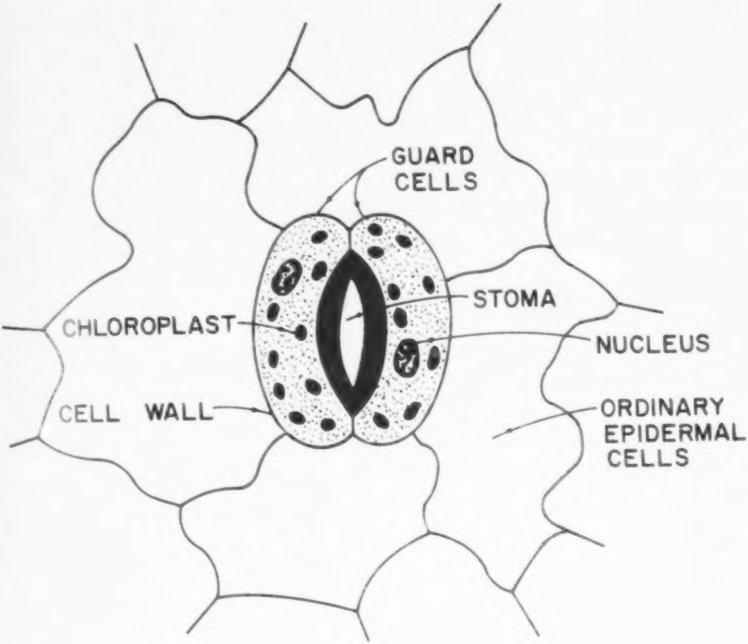

Figure 15-5.—Portion of leaf epidermis. (Drawing after Fuller and Tippo 1949).

Size, frequency (tables 15-1 and 15-2), and rapidity of response of stomata to stimuli vary significantly among species, giving rise to species variations in transpiration rates. Kozlowski et al. (1974) attribute the higher transpiration rate of white ash (compared to *Acer saccharum* Marsh.) to its larger (though fewer) stomata, less efficient stomatal closure, and less effective cutinization. Also, stomatal response to changes in humidity and wind velocity is faster in sugar maple than in white ash. In white ash, red maple, northern red oak, and yellow-poplar, stomata open faster than they close in response to changes in light intensity; in some other species the reverse is true (Woods and Turner 1971; Davies and Kozlowski 1974; Davies et al. 1974).

TABLE 15-1.—*Stomatal distribution and size in fourteen southern Appalachian hardwoods*[1] (Data from Carpenter and Smith 1975)

Species	Distribution		Size	
	Upper epidermis	Lower epidermis	Length of overall stomatal apparatus	Length of pore
	Number/cm²		*µm*	
Ash, white	0	12,973	22	17
Elm, American	0	23,012	18	12
Hickory, mockernut	0	24,006	25	10
Hickory, shagbark	[2]	34,943	25	10
Hackberry	0	27,273	13	6
Maple, red	0	70,455	35	32
Oak, black	0	40,530	50	24
Oak, chestnut	0	66,193	19	8
Oak, northern red	[2]	68,182	23	9
Oak, post	0	42,424	32	14
Oak, scarlet	[2]	75,959	17	5
Oak, white	0	51,420	20	10
Sweetgum	0	22,443	17	11
Yellow-poplar	0	28,409	18	10

[1] All mature trees except hackberry and scarlet oak which were seedlings.
[2] Not determined.

TABLE 15-2.—*Number and length of stomata at two locations on lower surfaces*[1] *of sun leaves of saplings of eight hardwood species.* (Data from Brady[2])

Species	Number[3]		Length of pore[3]	
	Between veins	Along midrib	Between veins	Along midrib
	Number/mm²		*µm*	
Ash, green	369	398	19.4	19.4
Elm, winged	871	864	16.7	17.0
Maple, red	975	1,002	11.2	11.0
Oak, blackjack	971	991	16.5	16.0
Oak southern red	1,600	1,627	11.7	12.0
Oak, water	972	990	14.5	14.5
Sweetbay	881	946	10.9	10.7
Sweetgum	575	575	14.8	15.0

[1] Upper surfaces had no stomata.
[2] Brady, H. A. 1971. Foliar characteristics of six species of hardwoods. Final Reports FS-SO-1102-4.35 and 4.49. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Alexandria, La. 102 p. and 105 p.
[3] Each value is based on data from nine saplings (4-inch dbh and smaller) sampled from the Kisatchie National Forest in Louisiana.

Carpenter and Smith (1975) counted and measured stomata in shade leaves in lower crowns of 50 Appalachian tree and shrub species, of which 14 are common on southern pine sites (table 15-1). Only shade leaves collected from the lower interior crown were studied. They found that stomata are mostly absent in the upper epidermis. In the lower epidermis of the 14 species, stomata varied from 12,973/cm^2 in white ash to 70,455/cm^2 in red maple. Longest pore lengths among stomata of these 14 species were found in red maple (32 μm); the smallest were in scarlet oak (5 μm). They also observed that mesic species had fewer stomata per unit of leaf surface than xeric species, and that stomatal frequency was not related to shade tolerance. Brady's data[3] on sun leaves from saplings in Louisiana (table 15-2) indicate more stomata per cm^2 for the two species common to both studies, but shorter pore lengths for red maple and longer ones for sweetgum. Kowslowski (1971) notes that leaves exposed to the sun have more stomata than shaded leaves from the same species.

Stone (1961) studied stomata size among 16 species of *Carya*, mostly collected in Louisiana. Among the four true hickories discussed in this text, shellbark had the smallest stomata pores and mockernut the largest, as follows:

Hickory species	Length	Width	Area
	----μm	---	μm^2
Shellbark	20	16	323
Shagbark	23	19	427
Pignut	26	22	586
Mockernut	27	23	618

In leaves of most tree species, stomata are confined to the lower epidermis (table 15-1), and the cutin layer (**cuticle**) is thicker on the upper epidermis, especially over midribs (table 15-3). Both characters reduce the drying action of sunlight striking upper leaf surfaces.

In ten of the species described and keyed in chapter 3, **hairs** occur as outgrowths of epidermal cells on lower leaf surfaces (fig. 15-6). Pine-site hardwoods displaying such pubescence include black, blackjack, cherrybark, chestnut, and southern red oaks, mockernut and shagbark hickories, sweetbay, red maple, and green ash.

In three of the species under study, lower leaf surfaces are **glaucous,** i.e., covered with a waxy or powdery bloom, usually white (fig. 15-7).

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[3] Brady, H. A. 1971. Foliar characteristics of six species of hardwoods. Final Reports FS-SO-1102-4.35 and 4.49. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Alexandria, La. 102 p. and 105 p.

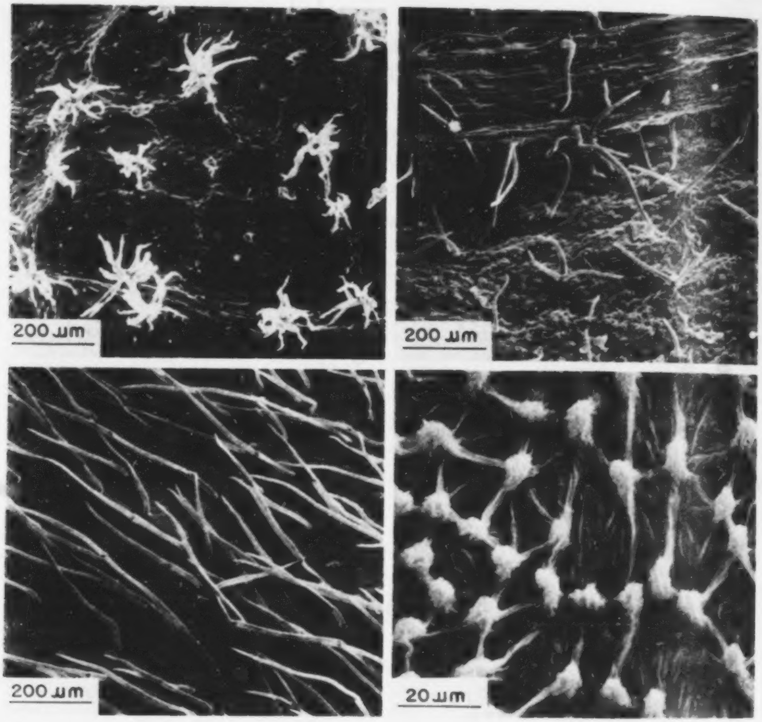

Figure 15-6.—Scanning electron micrographs of pubescence on lower surfaces of leaves of four southern hardwoods. (Top left) Blackjack oak. (Top right) Mockernut hickory. (Bottom left) Sweetbay. (Bottom right) Green ash. (Photos from files of C. W. McMillin, U.S. Dep. Agric. For. Serv.)

Mesophyll.—The bulk of hardwood leaf tissue is mesophyll (fig. 15-3), consisting of thin-walled parenchyma cells containing numerous chloroplasts. These are the food-making cells of leaves. The mesophyll cells nearest the upper epidermis are cylindrical and loosely packed at right angles to the leaf surface. These constitute the **palisade** layer of the mesophyll. In most plant leaves there are one or two such palisade layers just beneath the upper epidermis. Jackson (1967) observed that in leaves from 27 Georgia hardwoods the relative thickness of palisade tissue in sun and shade leaves is a good indication of tolerance of the species for shade. In tolerant or intermediate species, this thickness in sun leaves was up to 1.5 times that in shade leaves; in intolerant species palisade tissue in sun leaves was 1.8 to 3.0 times that in shade leaves.

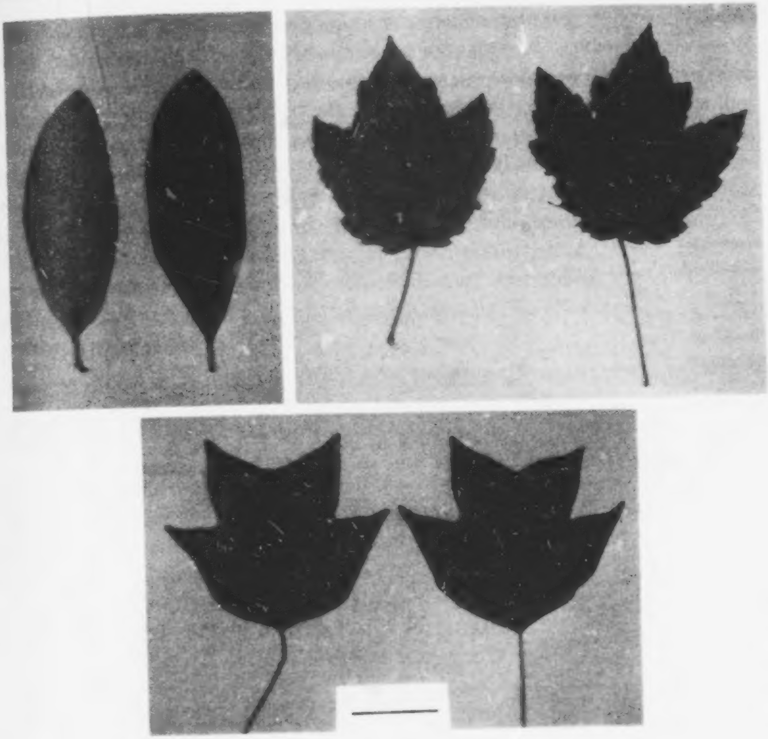

Figure 15-7.—Comparison of upper leaf surfaces and lighter-colored glaucous lower surfaces of leaves of three southern hardwood species. (Top left) Sweetbay. (Top right) Red maple. (Bottom) Yellow-poplar. Scale mark shows 2 inches.

TABLE 15-3.—*Cuticle thickness between veins and over the midrib on upper and lower leaf surfaces of eight southern hardwoods.* (Data from Brady[1])

Species	Between veins[2]		Over midrib[2]	
	Upper	Lower	Upper	Lower
	µm			
Ash, green	1.7	1.1	2.2	2.1
Elm, winged	1.6	1.0	1.7	1.5
Maple, red	2.3	1.3	3.2	2.5
Oak, blackjack	3.5	1.7	3.3	2.7
Oak, southern red	3.5	1.4	3.1	2.5
Oak, water	2.3	1.2	2.6	2.0
Sweetbay	2.2	1.2	4.2	3.5
Sweetgum	1.9	1.2	2.6	2.0
Average	2.4	1.3	2.9	2.4

[1] Brady, H. A. 1971. Foliar characteristics of six species of hardwoods. Final Reports FS-SO-1102-4.35 and 4.49. U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Alexandria, La. 102 p. and 105. p.

[2] Each value is based on data from sun leaves on nine saplings (4-inch dbh and smaller) sampled from the Kisatchie National Forest in Louisiana.

Below the palisade cells is a second group of parenchyma cells of different form and arrangement. These cells, called the **spongy layer,** vary in shape and are so loosely packed that there are numerous air spaces among them. Like the palisade cells, they contain chloroplasts and thus are food-making cells. The air spaces connect with the spaces underlying the stomata, and thus facilitate the diffusion of gases within the leaves.

Veins.—The veins are extensions of the vascular bundles of the petiole into the leaf blades (figs. 15-2 and 15-3). They branch through the mesophyll tissues, and are surrounded by the mesophyll cells. In pine-site hardwoods, the main veins are raised on lower leaf surfaces. Among the eight species listed in table 15-2, vein relief on lower leaf surfaces is particularly prominent in water oak, winged elm, and green ash. On the upper surfaces of red maple leaves veins are sunken, while on those of blackjack, water, and northern red oak and sweetbay they are slightly raised; the upper surfaces of sweetgum, winged elm, and green ash leaves are relatively smooth over veins (Brady[3]).

Each vein is made up of both xylem (vessels and tracheids) and phloem (chiefly sieve tubes). The xylem, usually uppermost, conducts water and minerals into leaf parenchyma; phloem conducts elaborated foods to petioles, stems, and roots. Each vein is surrounded by bundle sheath cells, which aid in conduction; in larger veins some of these cells are thickened to increase support (fig. 15-3). Leaf veins branch until veinlets reach most mesophyl cells (fig. 15-2); there may be as many as 25,000 veinlet endings per square inch of leaf surface. Readers interested in the ontogeny of veins and their form in mature yellow-poplar will find Pray's (1954, 1955) discussions useful.

Veins and petioles of leaves contain some fibers (fig. 15-8), but on a weight basis the fiber content of most leaves is very small.

The leaves of the southern hardwoods that are the subject of this text—except for sweetbay which is evergreen—fall from the branches that bear them at the end of their growing season; i.e., they are **deciduous.** In autumn, perhaps triggered by shorter days, certain cells at the petiole base—the abscission layer—develop thin walls. This layer soon disintegrates, and the vascular bundles of the petiole break. Meanwhile, as the abscission layer disintegrates, cork cells form just below the abscission layer, affording protection to the leaf scar. In species such as some red oaks, which retain dead leaves until late winter, an abscission layer may not form or the tough vascular bundles may prevent the petiole from breaking.

LEAF SIZE AND VARIATION

Average surface area of individual leaves varies widely among hardwood species. Leaves of blackjack oak from central Louisiana average nearly six times the area of those from winged elm, and the compound leaves of green ash are more than three times as large as blackjack oak leaves (table 15-4).

Average area of individual leaves may vary with site; for example, small southern red oaks in Louisiana had leaves averaging 51 cm^2 in area (table 15-4), while those measured in the Tennessee Valley averaged 45 cm^2 (table 15-5). Leaf area may also vary with year; white oak leaves in the Tennessee Valley sampled in 1948 averaged 35 cm^2, while those sampled in 1949 averaged 45 cm^2 in area (table 15-5). Data of Rothacher et al. (1954) showed no clear relationships between time in the growing season and average leaf area or weight (table 15-5).

In a Tennessee study of yellow-poplar and white oak trees averaging 13 inches and 18 inches dbh respectively, Whittaker et al. (1963) found that leaves in the upper crown had less area than those in the lower crown; yellow-poplar leaves had average area of 91.5 cm^2, while those of white oak averaged 38.8 cm^2.

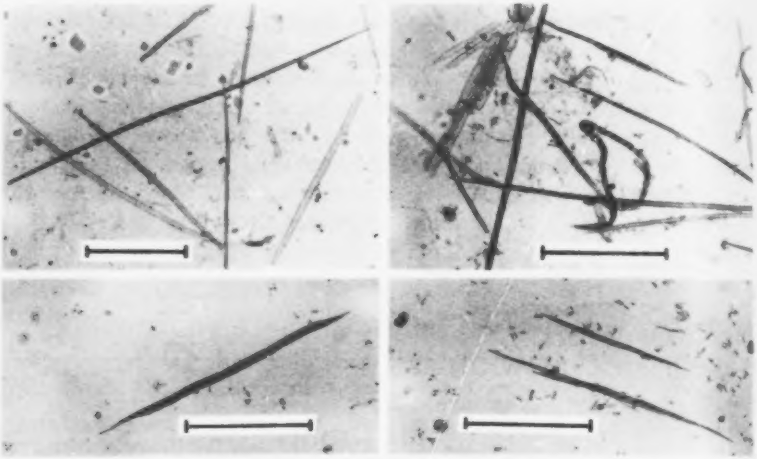

Figure 15-8.—Macerated tissue of sweetgum (top) and white oak (bottom) leaves, including petioles; prepared by 7-day treatment with equal parts of glacial acetic acid and 6-percent hydrogen peroxide at 60°C. Scale marks show 0.5 mm.

TABLE 15-4.—*Surface area and thickness of leaves from saplings of eight species of southern hardwoods sampled from April and May through August*[1] (Data from Brady[2])

Species	Leaf area	Leaf thickness Between veins	 Over midribs
	Cm²	µm	
Elm, winged	14	89	366
Oak, water	20	116	559
Maple, red	34	90	629
Sweetgum	44	166	671
Oak, southern red	51	134	909
Sweetbay	60	148	789
Oak, blackjack	79	149	1,181
Ash, green	268	96	552

[1] Each value is based on data from sun leaves on nine saplings sampled from the Kisatchie National Forest in Louisiana. Saplings measured up to 4 inches in dbh.

[2] Brady, H. A. 1971. Foliar characteristics of six species of hardwoods. Final Reports FS-SO-1102-4.35 and 4.49 U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Alexandria, La. 102 p. and 105 p.

TABLE 15-5.—*Average surface area (one side) and ovendry weight of individual leaves from trees of nine hardwood species grown in the Tennessee Valley and sampled three times in the growing season during each of 2 years.*[1] (Data from Rothacher et al. 1954)

Species and time in growing season	Leaf area 1948	 1949	Leaf weight 1948	 1949
	Cm²		*Grams*	
Hickory, mockernut				
Early	232	115	1.51	0.80
Mid	—	120	—	1.69
Late	178	75	1.94	.82
Hickory, pignut				
Early	108	136	.47	.88
Mid	—	153	—	1.35
Late	104	96	.78	.62
Oak, black				
Early	79	69	.64	.51
Mid	95	94	.74	.83
Late	93	61	.84	.53
Oak, chestnut				
Early	70	44	.32	.24
Mid	51	63	.35	.45
Late	58	53	.34	.43
Oak, post				
Early	62	—	.46	—
Mid	40	49	.38	.51
Late	60	—	.74	—
Oak, scarlet				
Early	41	55	.33	.49
Mid	56	52	.50	.44
Late	63	48	.45	.46

Table continued on next page.

TABLE 15-5.—*Average surface area (one side) and ovendry weight of individual leaves from trees of nine hardwood species grown in the Tennessee Valley and sampled three times in the growing season during each of 2 years.*[1] (Data from Rothacher et al. 1954) —Continued

Species and time in growing season	Leaf area		Leaf weight	
	1948	1949	1948	1949
	-----*Cm²*-----		--- *Grams* ---	
Oak, southern red				
Early	45	55	.35	.49
Mid	46	41	.52	.41
Late	38	46	.33	.42
Oak, white				
Early	32	57	.20	.38
Mid	36	50	.24	.35
Late	38	28	.23	.19
Tupelo, black				
Early	22	26	.12	.15
Mid	22	23	.12	.15
Late	—	25	—	.11

[1] Dbh of trees sampled varied from about 2 to 11 inches; they were selected from forest stands in Tennessee counties of Anderson, Cumberland, and Henderson and in Fannin County of Georgia. The number of branches sampled per species varied from 27 to 93.

Leaf thickness also varies greatly among species, e.g., when measured between veins, leaves of winged elm, red maple, and green ash are significantly thinner than those of sweetbay, sweetgum, and the three oaks listed in table 15-4. When measured over midribs, blackjack oak leaves are about three times as thick as those from winged elm.

As seen from figures 3-33 through 3-58 and 15-2, leaf shapes vary distinctively among species. Within-species variations are also substantial, but such variation in the pine-site hardwoods has been little studied. Figure 15-9 shows some variations observed among sweetgum, water oak, and yellow-poplar.

Within-tree variations of leaf shape are also common. Smith (1967) found that in sweetgum, each twig produces two kinds of leaves. Early spring leaves have relatively shallow lobes, whereas late leaves are more deeply lobed and generally have shorter petioles (fig. 15-9). Dendrologists who study the red oaks of the South are all aware of the within-tree variations in leaf shape that frequently make identification of these species difficult.

Readers interested in the methodology of determining leaf areas and thickness will find Chaney (1970), Gist and Swank (1974), Ulliman and Hatch (1978) and Wargo (1978) useful.

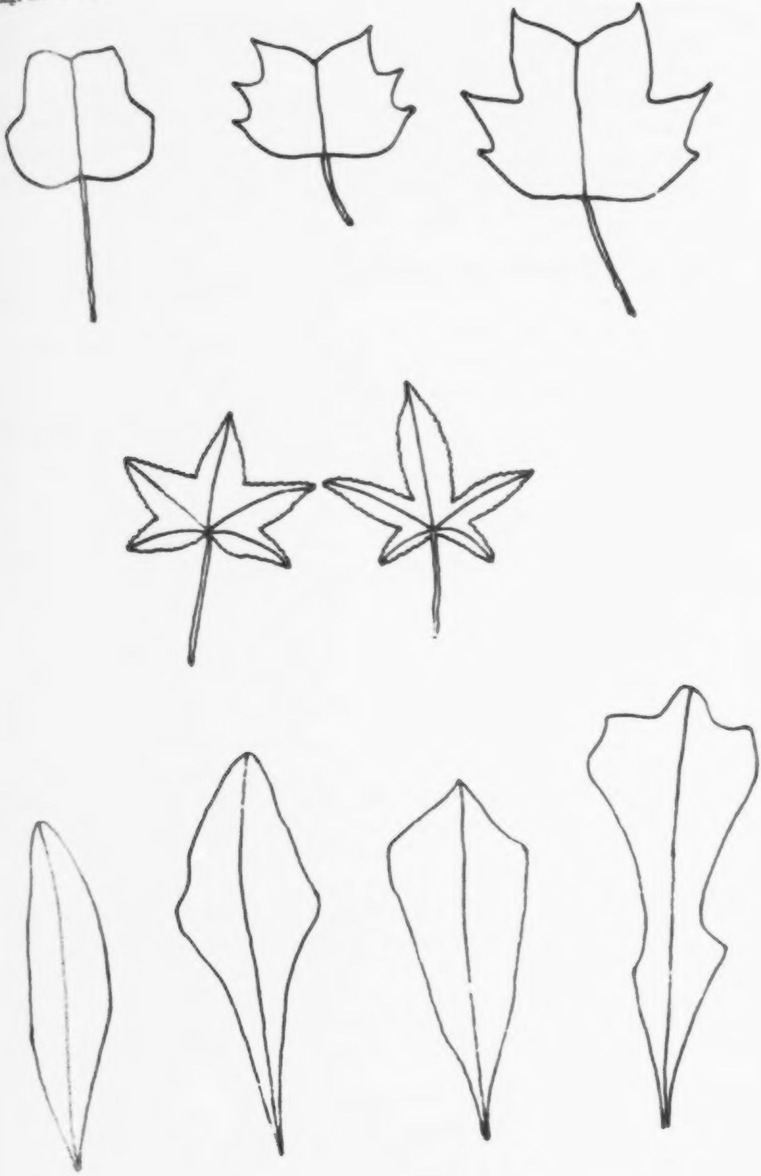

Figure 15-9.—Within-species variations in shapes of leaves. (Top) Yellow-poplar. (Drawing after Kellison 1967.) (Center) Sweetgum. (Drawing after Smith 1967.) (Bottom) Water oak. (Drawing after Brady[3].)

15-2 FOLIAGE QUANTITY

Forest managers considering utilization of foliage must be concerned with the relationship between foliage quantity and wood production, foliage proportion of complete-tree biomass, annual production of foliage per tree and per acre, and the weight and rate of decomposition of litter on the forest floor.

FOLIAGE QUANTITY RELATED TO WOOD PRODUCTION

In a study of oak stands in the Tennessee Counties of Anderson, Cumberland, and Henderson, and in Fannin County, Georgia, Rothacher et al. (1954) found that the total number of leaves averaged nine million per acre with minor variation. The same study indicated that **leaf area index** (LAI), acres of leaf surface (one side only) per acre of land, varied from a maximum of 5.2 in mid-growing season to 4.3 in the late season. Early in the growing season, minimum weight of foliage was 1.3 tons per acre (ovendry basis); in mid-season the minimum was 1.7 tons per acre.

Peak foliage biomass was determined by Harris et al. (1973) in another study of mixed hardwood stands in eastern Tennessee. In the oak-hickory, yellow-poplar, chestnut oak, and shortleaf pine forests of the Walker Branch watershed, maximums occurred at mid-season and ranged from 3.2 to 3.9 tons per acre (ovendry basis).

Leaf area index varies with forest type, season, and location. In a post oak-blackjack oak forest in central Oklahoma, Johnson and Risser (1974) found that LAI in vegetation larger than 2.5 cm dbh went rapidly from zero at the time of bud break in mid-April to 4.2 in early May, increased more slowly to a peak of 4.8 in early June, and then decreased slowly to 3.8 at the end of the growing season in late October. Monk et al. (1970) reported the LAI of an oak-hickory forest in the Piedmont region of Georgia at 3.5 to 4.0.

Crown diameter related to dbh.—Crown size is an indirect measure of foliage area and has been found related to bole diameter of open-grown and forest-grown hickories and oaks (white, black, northern red, and scarlet) in southern Illinois; the relationship between average crown width and bole dbh appeared to be independent of site, crown class, and species, as follows (Minckler and Gingrich 1970):

Dbh	Crown diameter
Inches	*Feet*
4	11
8	18
12	24
16	31
20	38

Number of leaves related to dbh and branch diameter.—Rothacher et al. (1954) found logarithmic relationships between dbh and numbers of leaves on black, scarlet, and white oaks grown in the Tennessee Valley; they also observed similar relationships between branch diameter and number of leaves on the branch (fig. 15-10).

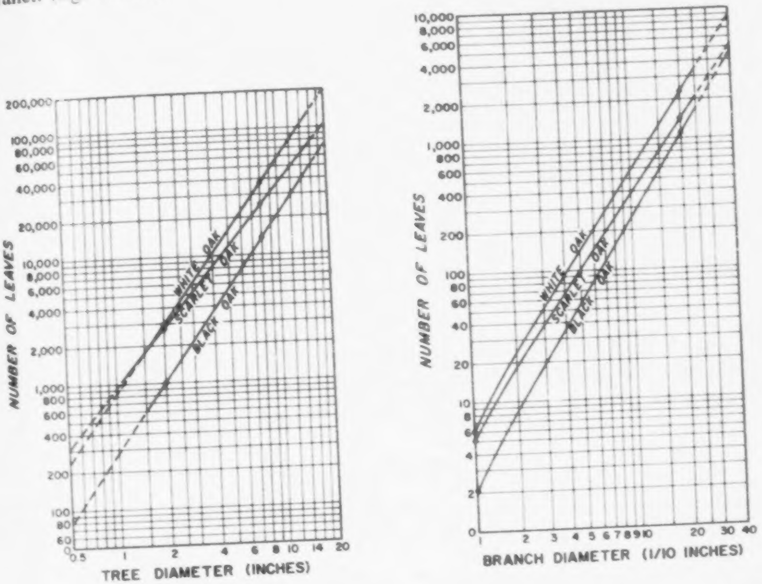

Figure 15-10.—(Left) Logarithmic relationship of number of leaves to dbh on trees of three oak species. (Right) relationship between number of leaves per branch and branch diameter outside bark. (Drawing after Rothacher et al. 1954.)

Dry leaf weight related to tree height and dbh.—Young and Carpenter (1967) determined the ovendry and fresh green weight of foliage on about 15 red maple trees growing in Maine and related these weights to the weights of the complete trees including below-ground as well as above-ground portions. Weight of ovendry foliage varied from 0.8 gram on 1-foot-high trees to 751 grams on 35-foot-high trees; the relationship of foliage weight to height was curvilinear (table 15-6).

Monk et al. (1970), in a study of numerous hardwood species growing in the Georgia Piedmont, observed a curvilinear positive relationship between tree dbh and both leaf weight and leaf surface area; larger trees had leaves that weighed more per unit of surface area than small trees (table 15-7).

Day and Monk (1974) used data from Sollins and Anderson (1971) to estimate foliage, branch, and stem weight by equations of the form: $\log_{10} Y = A + B \log_{10} X$. In this equation Y = ovendry weight of foliage per tree, kg; X = diameter, cm (breast height for larger trees and at ground level for hardwoods <2.5 cm dbh). Regression coefficients for this equation appropriate for mixed hardwood species of the Watershed at Coweeta Hydrologic Laboratory, Franklin, N.C., are as follows:

Tree size and component	A	B	r
⩾ 2.5 cm dbh			
Leaves	−1.5799	1.7719	0.94
Branches	−1.4472	2.2350	.96
Stem	−1.0382	2.3885	.98
< 2.5 cm dbh			
Leaves	−1.8789	2.1716	.96
Stem	−1.3620	2.7172	.98

TABLE 15-6.—*Red maple foliage weights and proportions of weights of complete trees forest-grown in Maine to heights of 1 to 35 feet.* (Data from Young and Carpenter 1967)

Tree height (feet)	Foliage weight		Foliage proportion of complete-tree weight	
	Fresh	Ovendry	Fresh	Ovendry
	Grams		*Percent*	
1	2.1	0.8	46.7	40.0
3	17.7	6.7	29.2	22.7
5	47	18	22.0	16.8
10	178	67	14.4	10.4
15	388	147	10.9	7.9
20	673	256	8.9	6.4
25	1,032	393	7.6	5.4
30	1,464	558	6.6	4.7
35	1,967	751	5.9	4.2

[1] Data based on a destructive sample of about 15 trees. Complete-tree weights include below-ground as well as above-ground tree portions.

TABLE 15-7 —*Foliage weight, tree weight, foliage area, and the reciprocal of leaf specific density related to dbh of trees of 11 hardwood species grown in the Georgia Piedmont*
(Data from Monk et al. 1970)

Species	Tree dbh	Foliage weight (ovendry)	Tree weight (ovendry[1]	Foliage proportion of weight	Foliage surface area	Reciprocal of leaf specific density[2]
	Cm	--------*Kg* --------		*Percent*	M^2	Cm^2/g
Hickory, pignut	2.8	0.12	1.8	6.7	2.50	202
Hickory, pignut	3.0	.13	1.8	7.2	—	—
Tupelo, black	3.0	.10	2.1	4.8	2.32	233
Tupelo, black	3.5	.10	2.4	4.2	2.08	219
Sweetgum	4.2	.22	2.5	8.8	4.12	187
Oak, white	5.5	.43	6.1	7.0	8.89	205
Hickory, mockernut	5.5	.49	10.4	4.7	9.58	195
Oak, post	8.3	.53	14.9	3.6	8.23	156
Sweetgum	10.5	1.07	18.9	5.7	16.39	152
Oak, black	11.2	1.18	23.9	4.9	17.50	148
Yellow-poplar	12.5	1.71	48.3	3.5	31.16	182
Oak, northern red	12.5	2.49	69.1	3.6	26.07	104
Oak, white	14.0	4.13	86.7	4.8	69.87	169
Oak, white	16.8	4.13	146.3	2.8	57.41	139
Oak, white	19.3	5.69	160.4	3.5	80.20	141
Oak, white	21.0	8.70	291.2	3.0	96.42	111
Oak, scarlet	26.7	17.07	457.3	3.7	164.19	96
Oak, post	36.0	25.66	897.4	2.9	235.40	92

[1] Above-ground tree portions only.
[2] Ovendry weight basis.

Green leaf weight related to dbh, crown length, and tree height.—Schlaegel[4] found that weight of green leaves on a tree can be predicted from knowledge of dbh (inches) and crown length (feet) according to the equation:

$$\text{Green leaf weight, pounds} = a + b\,(dbh^2 \times \text{crown length}) \qquad (15\text{-}1)$$

where the regression constants are as follows:

Species	a	b	Sy·x	R^2
			Pounds	
Green ash	35.9	0.00238	48	0.32
Sweetgum	55.7	.00390	52	.63
Sugarberry	14.4	.00717	52	.47

Harris et al. (1973) studied the forests on the Walker Branch watershed of eastern Tennessee, which are comprised principally of four types: shortleaf pine, yellow-poplar, oak-hickory, and chestnut oak. After pooling data on all hardwood species, they concluded that the weight of leaves on these trees has a curvilinear positive correlation with tree dbh (fig. 15-11). Weight of fresh green leaves of red maple are curvilinearly related to tree height (table 15-6).

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[4] Personal communication March 1979 with Bryce Schlaegel, U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Stoneville, Miss.

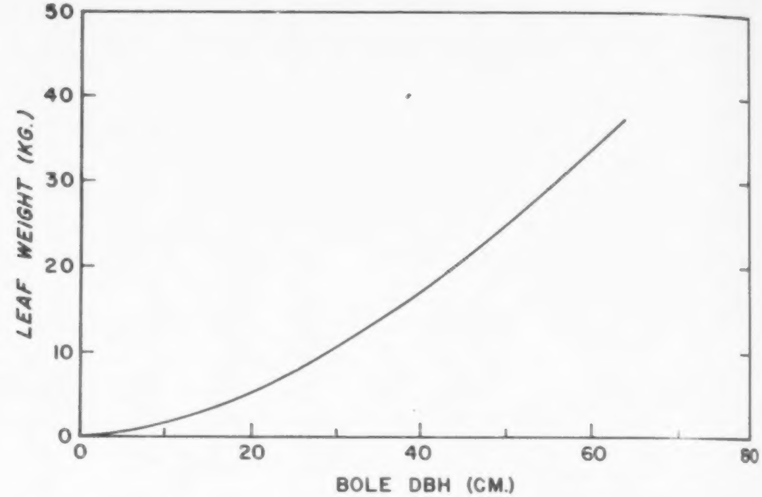

Figure 15-11.—Relationship between leaf weight (ovendry basis) per tree and tree dbh. The relationship is derived from pooled data from all hardwood species on the Walker Branch watershed in eastern Tennessee. (Drawing after Harris et al. 1973.)

Leaf area and weight related to tree biomass production.—Trees with large leaf areas increase in weight faster than those with lesser leaf areas; in greenhouse-grown seedlings, Newhouse and Madgwick (1968) found that the increase in weights of complete 16- to 20-week-old seedlings (ovendry basis) varied from 21 to 31 g/m^2 of leaf area, as follows:

Species	New assimilation rate
	g/m^2
Yellow-poplar	23
American elm	24
Red maple	31

In yellow-poplar stands varying in basal area and containing trees 28 to 74 years old, Madgwick and Olson (1974) found that leaf area index was linearly related ($R^2 = 0.54$) to annual volume growth of stems (6-inch stump to tip) including bark (fig. 15-12).

Zavitovski et al. (1974) concluded that annual production of bole-branch weight in hardwoods has a positive linear correlation ($R^2 = 0.54$) with leaf weight up to about 6 metric tons per hectare (fig. 15-13).

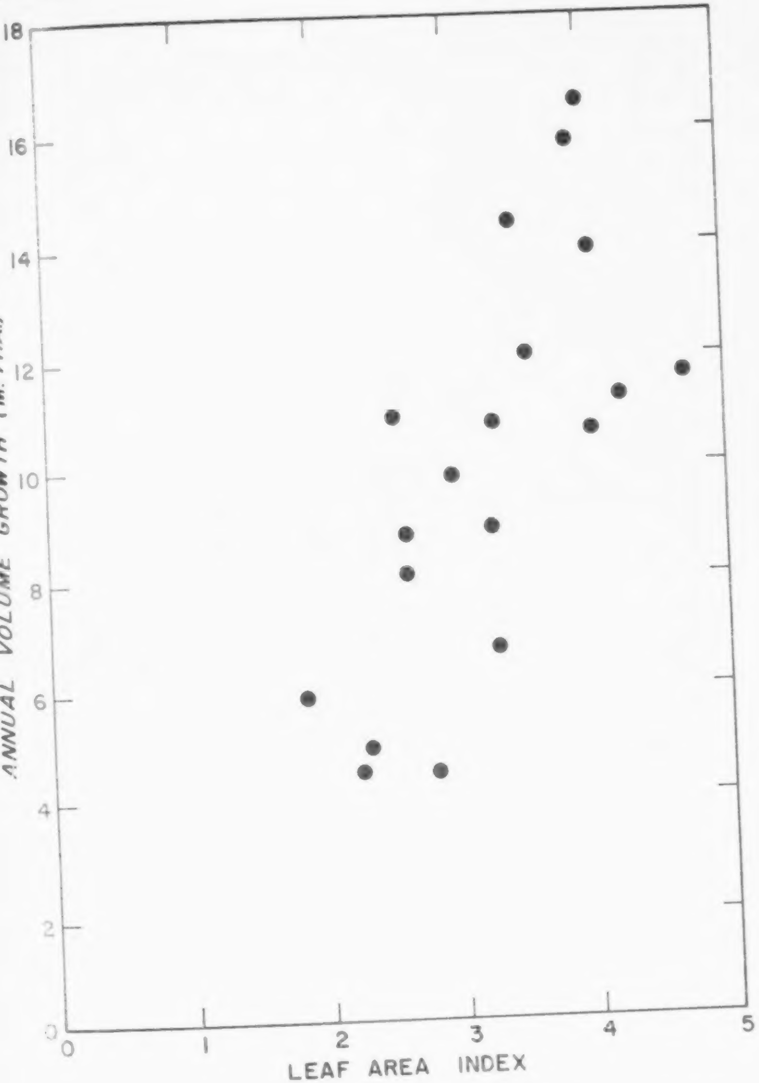

Figure 15-12.—Relationship between current annual stem volume increment (to stem tip and including bark) and leaf area index in yellow-poplar. 10 M^3/ha is the equivalent of 143 ft^3/acre. (Drawing after Madgwick and Olson 1974.)

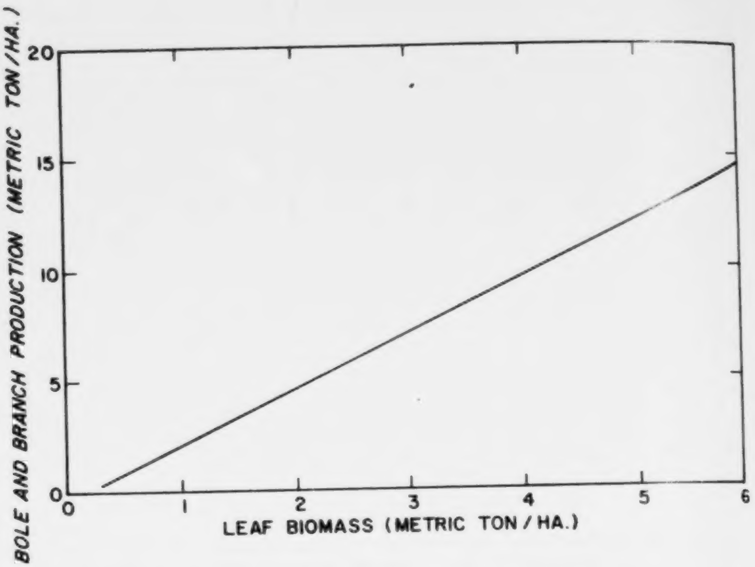

Figure 15-13.—Relationship between annual production of bole-branch weight (ovendry basis, bark included) and leaf biomass in hardwoods. 10 metric tons per hectare is the equivalent of 8,926 pounds per acre. (Drawing after Zavitovski et al. 1974.)

FOLIAGE PROPORTION OF TREE BIOMASS

The mixed-species forest studied by Harris et al. (1973) on the Walker Branch watershed in eastern Tennessee had dry foliage weights ranging from 2.1 to 6.9 percent of that of the complete trees, depending principally on diameter class (table 15-8); on an area-average basis, the shortleaf pine type stands had the greatest percent of their biomass in foliage (3.8 percent) and the oak-hickory type least (3.4 percent).

Manwiller's[5] analysis of three 6-inch trees of each of 23 species of hardwoods growing on southern pine sites indicate that foliage weight contributes from 1.4 to 4.5 percent of complete-tree weight (ovendry basis) depending on species (table 15-9); green ash had least percent foliage, and red maple most.

Johnson and Risser (1974), in a study of typical stands of post oak and blackjack oak in central Oklahoma, found that foliage comprised 2.2 percent of above- and below-ground tree biomass (ovendry basis). In the sample plots, canopy height was about 45 feet; trees had a range of diameters but did not exceed 18 inches in dbh.

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[5] Manwiller, F. G. Unpublished data in Study File FS-SO-3201-1.59, U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Pineville, La.

TABLE 15-8.—*Foliage portion of complete tree biomass by tree dbh classes in stands of four types on the Walker Branch Watershed in eastern Tennessee* (Data from Harris et al. 1973)

Forest association	Foliage proportion[1]		
	1.3 to 8.9 cm	8.9 to 24.1 cm	>24.1 cm
	Percent, ovendry basis		
Chestnut oak	6.9	3.4	2.1
Oak-hickory	6.6	3.8	2.2
Yellow-poplar	6.8	3.7	2.2
Shortleaf pine	6.7	3.6	2.3

[1] Percent of above- and below-ground tree parts including large lateral roots to a radius of 60 cm. Each value is based on a sample of 24 to 44 trees.

With data from about 15 red maple trees grown in Maine, Young and Carpenter (1967) used regression analyses to correlate foliage proportion of complete-tree-weight—including above- and below-ground portions—to tree height. Foliage proportion (ovendry basis) decreased with increasing tree height, i.e., from 40 percent for a 1-foot-high tree to 4.2 percent for a 35-foot-high tree (table 15-6).

Data on red maple, scarlet oak, white oak, and yellow-poplar, expressed as foliage proportion of above-ground biomass (ovendry basis) are given in table 15-10. Weight proportions of fresh green foliage on white oak and chestnut oak are given for a range of tree diameters in table 15-11.

In a study of Georgia Piedmont hardwoods, Monk et al. (1970) found that for all species, the proportion of foliage weight to the weight of all above-ground tree parts tended to be higher for small trees; those 3 to 4 cm in dbh had 4 to 9 percent of the tree weight in foliage, while most of those 17 to 36 cm in dbh had only 3 to 4 percent (table 15-7).

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TABLE 15-9.—*Green (and ovendry) foliage weight, and proportion of complete-tree weight, for 6-inch hardwoods grown on southern pine sites* (Data from Manwiller[1])[2]

Species	Tree dbh	Foliage weight[3]	Proportion of complete-tree weight with lateral roots severed at two radii[3]	
			3-foot	1-foot
	In	*Lbs*	*Percent*	
Ash, green	5.9	7.1 (2.5)	2.4(1.4)	2.5(1.5)
Ash, white	6.0	15.9 (7.6)	3.9(2.9)	4.2(3.0)
Elm, American	6.1	15.8 (5.3)	3.8(2.4)	4.0(2.5)
Elm, winged	6.1	11.8 (6.9)	2.8(2.7)	3.0(2.9)
Hackberry[4]	6.2	10.4 (5.9)	3.4(3.3)	3.7(3.5)
Hickory, sp.	5.8	14.6 (5.4)	3.7(2.4)	4.0(2.5)
Maple, red	5.9	31.1(14.3)	5.4(4.5)	5.9(5.0)
Oak:				
black	6.0	12.9 (5.2)	3.3(2.3)	3.5(2.4)
blackjack	6.4	14.6 (7.1)	3.6(3.0)	4.1(3.3)
cherrybark	5.8	17.8 (9.9)	4.7(4.4)	5.0(4.6)
chestnut	6.0	15.8 (6.2)	3.6(2.4)	3.8(2.5)
laurel	5.7	10.4 (5.2)	2.6(2.2)	2.8(2.4)
northern red	6.2	13.6 (5.7)	2.7(2.0)	2.8(2.0)
post	6.1	10.8 (4.4)	2.6(1.8)	2.7(1.9)
scarlet	5.8	15.1 (6.4)	3.5(2.7)	3.7(2.8)
Shumard	6.8	26.9(14.2)	4.5(4.0)	4.8(4.2)
southern red	5.9	13.0 (6.1)	2.8(2.4)	3.0(2.6)
water	6.1	20.8(10.6)	3.9(3.4)	4.1(3.6)
white	6.2	20.4 (9.4)	3.5(2.9)	3.8(3.1)
Sweetbay	6.0	20.9 (7.4)	5.2(3.7)	5.6(4.0)
Sweetgum	6.1	21.7 (7.5)	5.7(4.3)	6.0(4.6)
Tupelo, black	6.2	22.4 (8.1)	5.2(3.7)	5.7(4.0)
Yellow-poplar	5.8	19.0 (6.2)	5.4(3.7)	5.8(4.0)

[1] Manwiller, F. G. Unpublished data in Study file FS-SO-3201-1.59, U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Pineville, La.

[2] Each value, with the following exceptions, is the average for three trees collected in Louisiana. The scarlet and chestnut oak trees came from Winston Co., Ala.; the northern red oak was from Montgomery Co., Ark., and the black oak from both the Alabama and Arkansas locations. Shumard oak data describe a single tree from Louisiana.

[3] The first value tabulated is based on green weight; the second value, in parentheses, is based on ovendry weight.

[4] Sugarberry.

TABLE 15-10.—*Foliage weight per tree and proportion of above-ground tree biomass (ovendry weight basis) of some hardwood species that grow in the South*

Species and tree dbh	Foliage weight (ovendry basis)	Foliage proportion	Reference
	Pounds	*Percent*	
Maple, red[1]			Ribe (1973)
1 inch	0.3	12.8	
2 inches	1.0	8.2	
3 inches	2.1	6.2	
4 inches	3.6	5.0	
5 inches	5.3	4.2	
6 inches	7.4	3.7	
Oak, scarlet[2]	—	5.5	Whittaker and Woodwell (1969)
Oak, white[2]	—	6.1	Whittaker and Woodwell (1969)
Oak, white[3]	—	2.1	Whittaker et al. (1963)
Yellow-poplar[4]	—	1.9	Whittaker et al. (1963)

[1] Trees were sampled in Maine.

[2] Trees were of all age classes in an oak-pine forest growing on Long Island, N.Y.

[3] Based on a 10-tree sample in eastern Tennessee; the trees averaged 96 years old and 17.6 inches in dbh. The value tabulated includes twigs.

[4] Based on 10-tree sample in eastern Tennessee; the trees averaged 75 years old and 13.4 inches in dbh. The value tabulated includes twigs.

ANNUAL PRODUCTION

Because leaves of all pine-site hardwoods discussed in this text (except sweetbay) fall in autumn and winter, annual production can be assessed as the weight of foliage on trees in mid-summer, or the weight of annual litterfall. Foliage weights on individual trees are best obtained from clipped leaves. Production per acre is more readily measured in litter traps. Results from the two methods should differ slightly due to withdrawal of some nutrients from foliage just prior to leaf fall.

TABLE 15-11. *Weight of fresh green foliage of chestnut and white oaks of various diameters, and foliage proportions of above-ground tree biomass (green weight basis)* (Data from Colannino 1976)[1]

Dbh (inches)	Tree height	Weight of leaves	Foliage proportion of above-ground tree biomass
	Feet	*Pounds*	*Percent*
	CHESTNUT OAK		
3.2	30.1	1.3	2.1
3.4	34.7	5.0	7.7
3.9	36.5	2.5	2.4
4.7	47.3	12.5	6.0
4.7	54.1	3.0	1.3
5.7	61.1	6.0	1.6
5.8	62.0	5.3	1.6
6.7	60.5	20.0	4.2
7.9	59.9	25.0	3.7
8.2	66.6	23.8	2.5
9.8	59.7	25.0	2.1
9.9	60.2	30.0	2.4
10.3	71.6	32.5	2.4
10.7	63.5	27.5	1.8
11.0	59.3	43.8	2.8
12.3	64.0	25.0	1.1
13.2	60.7	102.5	4.6
13.8	66.6	46.3	1.6
14.0	62.9	77.5	2.8
15.2	63.3	100.0	2.8
15.3	64.0	82.5	2.3
	WHITE OAK		
3.2	25.2	2.5	6.7
3.6	26.8	3.8	5.7
3.7	29.1	6.3	6.8
4.8	47.9	—	—
5.3	48.0	5.0	2.0
5.4	47.4	3.8	1.7
6.2	49.1	6.3	1.8
6.8	59.0	10.0	2.1
7.2	56.6	25.0	4.8
8.7	53.9	35.0	4.4
8.9	55.1	40.0	5.1
9.3	60.6	38.8	3.9
10.7	66.2	46.3	2.7
10.9	69.1	32.5	2.3
11.6	73.0	76.3	3.9
12.0	67.1	30.0	1.6
12.5	67.5	65.0	3.4
13.4	71.5	165.0	6.2
14.7	71.2	92.5	2.7
14.8	72.4	127.5	3.9
15.9	75.1	71.3	2.0

[1] Sampled in north-central West Virginia.

Weight of foliage on trees.—Table 15-9 gives the fresh and ovendry weights of foliage on 6-inch trees of most of the pine-site hardwood species. The variation among species is substantial; for example, the 5.9-inch green ash trees studied averaged about 2½ pounds of foliage per tree, whereas the 5.8-inch yellow-poplar trees had slightly over 6 pounds of foliage per tree (ovendry weight basis). Additional data on foliage weights related to tree dbh are given in tables 15-7 and 15-10.

Colannino (1976) correlated the weight of fresh green leaves on white oak and chestnut oak with dbh (inches) and crown volume (cubic feet), as follows ($R^2 = 0.71$):

$$\text{Fresh foliage weight, pounds} = (4.62616)(\text{dbh}) - (0.00145)(\text{crown volume}) - 17.92608 \qquad (15\text{-}2)$$

The equation, applicable to both species, is based on 21 trees of each, ranging from 3 to about 16 inches dbh in north-central West Virginia; tree height averaged 57 feet. Average foliage weights on trees more than 10 inches dbh were 78.5 and 59.7 pounds for white oak and chestnut oak respectively, constituting 3.2 and 2.5 percent of average whole-tree weight (table 15-11).

Foliage production per acre.—Executives considering the processing of foliage into products need data on annual foliage production per acre. Silviculturists concerned with nutrient balances in the forest also need data on annual leaf fall, and hydrologists are mindful of leaf fall as it affects litter accumulation and run-off of water. Table 15-12 summarizes the literature and indicates that annual production of foliage in southern upland hardwoods ranges from about 2,000 to about 5,000 pounds per acre per year (ovendry basis).

In addition to leaf fall, significant amounts of twigs drop annually to the forest floor. For example, Rochow (1974) reported twig fall in an upland oak stand in Boone County, Missouri, at 823 pounds per acre per year (ovendry basis). In thinned even-age (44 to 77 years) stands of yellow-poplar near Asheville, N.C., Olson (1971) observed a twig fall of 637 pounds per acre per year (ovendry basis). Metz (1952) found that uneven-age upland hardwoods—mostly hickory, yellow-poplar, red maple, and northern red oak—in the Calhoun Experimental Forest of Union County, S.C., had twig fall—including some bark and fruits—of 662 pounds per acre per year (ovendry basis).

Deer browse in stands of hardwoods growing on southern pine sites includes foliage and twigs of shrubs as well as some leaves and twigs of the trees that are the subject of this text. Readers interested in the volumes of deer browse produced in these forests are referred to the citations listed in section 15-5 under subsection WILDLIFE FOOD.

TABLE 15-12.—*Annual foliage production (ovendry basis) on a variety of stands of southern hardwoods*

Species and stand description	Annual foliage production	Reference
	Pounds/acre	
Oak-hickory, chestnut oak, yellow-poplar, and shortleaf pine stands in the Walker Branch watershed of eastern Tennessee	3,034 to 3,660	Harris et al. (1973)
Upland oak stands in eastern Tennessee	2,600	Blow (1955)
Upland oak stand in southeastern Missouri (Dent County)	4,200	Loomis (1975)
Oak stands in the Tennessee Counties of Anderson, Cumberland, and Henderson, and Fannin County in Georgia	2,600 to 3,400	Rothacher et al. (1954)
Post oak and blackjack oak in central Oklahoma; trees measured up to 18 inches in dbh	4,247	Johnson and Risser (1974)
Oak-pine forest, uneven aged, on Bent Creek Experimental Forest near Asheville, N.C.	2,850	Sims (1932)
Yellow-poplar in thinned even-aged (44 to 74 years) stands southeast of Asheville, N.C.	1,937	Olson (1971)
Upland hardwoods, mostly hickory with yellow-poplar and northern red oak in all age classes growing on the Calhoun Experimental Forest in Union County, S.C.	4,103	Metz (1952)
80-year-old, unmanaged, low-grade upland oak stand near Oxford, Miss. (mostly blackjack, white, and post oaks); trees were 2 to 13 inches in dbh, with average of 5.4 inches and 438 trees per acre.	4,000 to 5,000	Dickerson (1972)
Mixed hardwoods 1 to 14 inches in dbh sampled in Georgia's Piedmont region	3,889	Monk et al. (1970)
Mixed hardwoods on a relatively undisturbed watershed at Coweeta Hydrologic Laboratory, Franklin, N.C. (an estimate of leaf weight on trees based on sample plot data and regression analysis)	5,012	Day and Monk (1974)

WEIGHT OF LITTER ON THE FOREST FLOOR

Litter under hardwood forest canopies is comprised mainly of leaves, a sizeable proportion being contributed by understory plants (Thor and Nichols 1973). In the absence of fire, litter accumulation is determined by the rates at which it falls and decomposes. In dry northern climates where decomposition is slow, litter may accumulate to a depth of 1 foot or more. In humid equatorial regions decomposition may be so rapid that the forest floor is nearly bare of litter. In forests of the southern United States, litter accumulation is intermediate to these extremes.

Litter quantity is of interest to potential users of such material for energy or products. It is also of interest to hydrologists concerned with water runoff, physiologists and soil managers concerned with seedbed characteristics, and forest managers concerned with prescribed burns or protection against wildlife. Some data describing depth, weight, and components of litter on the forest floor under upland hardwoods in the South follow.

Harris et al. (1973) weighed foliage samples from the forest floor under four forest types in the Walker Branch Watershed of eastern Tennessee at intervals over 24 months; mean values were as follows (ovendry basis, foliage only, no twigs or wood):

Forest type	Weight of foliage on forest floor
	Pounds/acre
Shortleaf pine	9,700
Oak-hickory	7,800
Chestnut oak	6,200
Yellow-poplar	5,900

Dickerson (1972) measured the weight and depth of all the litter comprising the forest floor under an 80-year-old low-grade upland oak stand near Oxford, Miss.; the stand averaged 438 trees per acre measuring 2 to 13 inches in dbh, with average dbh of 5.4 inches. Results were as follows:

Time of sample	Ovendry weight	Depth of forest floor
	Pounds/acre	*Inches*
September 1964	10,600	0.4
December 1964	10,000	.3
March 1965	10,400	.2
June 1965	9,000	.1

Thor and Nichols (1973) determined components of litter under an upland hardwood stand at the Highland Rim Forestry Field Station in Franklin County, Tenn. Three oak species—southern red, post, and scarlet—were dominant in both overstory and understory. In unburned plots averaging 8,060 understory stems per acre (1 foot in height to 5 inches in dbh) for the years 1965 through 1972, average ovendry weights of litter components in January and February were as follows:

Component	Litter weight per acre	Proportion of total litter
	Pounds	*Percent*
Leaves	5,748	74
Twigs	1,151	15
Fruits	205	3
Grass	589	8
Total litter	7,693	100

On matched plots, burned annually, average weight of leaves was reduced to about 2,177 pounds per acre.

A pine-oak stand on the Bent Creek Experimental Forest in the southern Appalachian Mountains accumulated total litter averaging 7,900 pounds per acre (ovendry basis); of this, 6,300 pounds was leaf litter. The stand had been undisturbed for 10 years and had a crown density of 0.9 (Sims 1932).

Under stands of post oak and blackjack oak in central Oklahoma, Johnson and Risser (1974) found total litter—sampled down to mineral soil—averaging 10,767 pounds per acre (ovendry basis). The sample acre had a few old trees (up to 18 inches in dbh) in a dense canopy of young trees and saplings, about 40 feet high.

Metz (1954) sampled the forest floor in a hardwood stand in Union County, S.C., comprised mostly of 150-year-old hickory. The L layer, i.e., the top undecomposed layer of loose debris including branches, twigs, and recently fallen leaves, averaged 8,000 pounds per acre (ovendry basis); southern pine stands in the area had approximately double this weight of forest floor in two layers, 4,100 pounds in the L layer, and 12,600 pounds in the F (fermentation) layer below, which includes leaves still identifiable but stuck together and flat.

Weight of the forest floor litter varies with age of stand, but data expressing the relationship for southern hardwood forests are scarce. Crosby and Loomis (1974) observed that black oak forest floor fuelbeds under 20- and 40-year-old stands in southeast Missouri averaged respectively 6.4 and 8.3 tons per acre (ovendry basis) and 4.0 to 4.2 inches in depth. Loose litter averaged 2.0 and 2.9 tons per acre, respectively (ovendry basis) but was 3.3 inches in depth under both stands. Bulk density of loose dry litter averaged 0.33 and 0.49 lb/ft^3 and of total forest floor (i.e., including fermentation and humus layers) 0.89 and 1.10 lb/ft^3, respectively.

Litter decomposition rate.—Rates of litter decomposition are of interest to potential users because they limit the time during which fallen foliage must be collected. To forest managers, litter decomposition to humus and its ultimate mineralization are important in the cycle whereby nutrients are returned to trees. Initial decomposition of leaf litter is usually rapid, but tends to stabilize later at a slower rate. Decomposition is initiated by leaching of nutrients which support blooms of micro-organisms. Microarthropods and larger invertebrates mechanically hasten the process. The mesophyll of leaves decomposes most rapidly, followed by leaf epidermis and veins (Akhtar et al. 1976). Shade leaves are softer than sun leaves and decompose more rapidly (Heath and Arnold 1966).

Shanks and Olson (1961) observed a great range in rates accumulation of litter and humus in forests of the Great Smoky Mountains. Differing rates of breakdown related to litter species and environment account for most of the variation. During 1 year of exposure in nylon net bags secured to the forest floor, oak leaves decomposed faster than beech leaves, but not as fast as red mulberry leaves, as follows (ovendry basis):

Species	First-year weight loss
	Percent
American beech (*Fagus grandifolia* Ehrh.)	21
Sugar maple (*Acer saccharum* Marsh.)	32
Shumard oak	34
White oak	39
Red mulberry (*Morus rubra* L.)	64

Leaf litter of American elm decomposes more rapidly than that of white oak, northern red oak, and shagbark hickory. Under Missouri conditions, American elm leaves crumble readily after 18 months on the ground (Fowells 1965).

From data on a pine-oak stand in the Bent Creek Experimental Forest near Asheville, N.C., Sims (1932) concluded that normal accumulation of litter in all stages of decomposition weighs two or three times as much as that deposited in 1 year; he observed that more than 3 years are required for the disappearance of any 1 year's litter. Rochow (1974) analyzed litter decomposition under hardwood stands in Boone County, Mo., and concluded that turnover time, i.e. time to decompose, was 2.9 years for foliage and 4.3 years for woody litter; he computed that leaf litter weights attained an equilibrium steady state at a stand age of 13.2 years, but the woody component required 19.7 years to attain equilibrium. Climate as well as species composition affect the time required to reach a steady state, when weight of annual litter increment equals the weight loss through annual litter decay. Rochow (1974), interpreting data from Witcamp and Olson (1963), concluded that in Tennessee time to an essentially steady state ranged from 3.1 to 7.2 years for unconfined and confined oak leaf litter, respectively.

An oak-hickory forest in Georgia's Piedmont region had leaf litter weight about twice the weight of the standing crop of live foliage in summer (Monk et al. 1970).

In an upland oak stand in eastern Tennessee, Blow (1955) found that annual leaf fall added 1.3 tons of litter per acre to the forest floor (ovendry basis); total litter reached a peak of 5.4 tons in December following leaf fall, and then decreased to a fairly stable low August weight of 4.2 tons per acre (fig. 15-14).

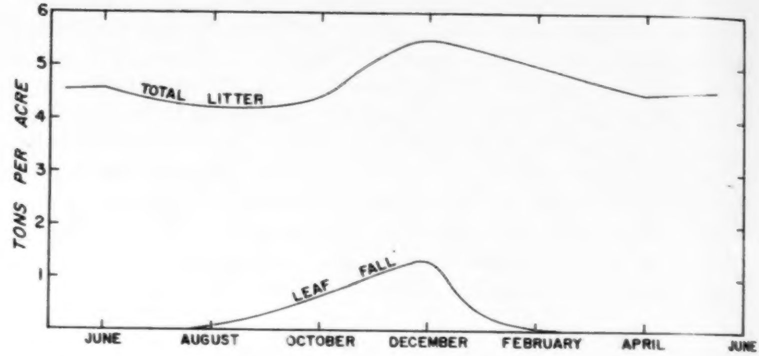

Figure 15-14.—Average weights (ovendry basis) of total litter and leaf fall over a 2-year period under an upland oak stand in eastern Tennessee. (Drawing after Blow 1955.)

Amount of organic material on the forest floor under a typical southeast Missouri oak stand was found by Loomis (1975) to vary about 2.1 tons per acre (ovendry basis) from season of greatest to season of least accumulation. This corresponded to the weight of annual litter fall. Accumulation was maximum at 7.5 tons per acre in November after leaf fall. Decomposition was rapid in summer; a minimum of 5.4 tons per acre was present in September before major leaf fall.

BULK DENSITY OF FOLIAGE

Technical foliage, i.e., leaves with attached stems up to ¼-inch in diameter, varies in bulk density with species, moisture content, degree of comminution, and degree of packing as follows (Vidrine and Woodson 1982):

Species and moisture content (O.D. basis)	Whole leaves		Hogged through ½-inch screen	
	Loose	Settled by vibration	Loose	Settled by vibration
	Pounds/cubic foot			
Sweetgum				
Green (211 percent)........	2.5	4.9	16.5	18.6
Air dry (25 percent)	.2	.5	4.6	5.9
Oak and hickory				
Green (144 percent)........	1.5	2.2	10.3	12.0
Air dry (16 percent)	.3	.6	4.3	6.2

15-3 FOLIAGE CHEMICAL COMPOSITION

Research centered on chemical composition of foliage from pine site hardwoods has been primarily concerned with nutrient balance in the forest. **Foliar analyses** for nitrogen and certain key mineral elements measure quantities of such elements available for return to the forest soil at leaf fall, and are indicators of soil fertility and of the relative ability of species and stand components to extract specific elements from the soil. Tabulations of foliar analyses primarily present data on ash, Ca, K, Mg, Mn, P, and N, but often include Cu, Fe, Na, S, and Zn. Investigations into the effectiveness of herbicides have also led to accumulation of data on leaf pH and wax content.

Chemical aspects of foliage use for animal food are discussed in section 15-5 FOLIAGE AS FOOD.

Only minor research effort has been expended to develop processes whereby chemicals in commercial quantities can be derived from foliage. Available data on this subject are discussed in section 15-6 OTHER USES OF FOLIAGE. These products include carotenoids, leaf oils, and chlorophyll-carotene paste.

GROWTH RELATED TO FOLIAR ANALYSIS

Detailed understanding of the role of foliar nutrient content in tree growth is needed if harvest of foliage for products is to avoid nutrient depletion in forest soils. Such data on pine site hardwoods are scarce.

The U.S. Department of Agriculture, Forest Service (1951) found highly significant correlation between the nitrogen content of white oak leaves and site index. On the poorest sites this content, probably the best measure of nitrogen availability, averaged less than 1.8 percent. On the better sites, as determined by site index, nitrogen content of leaves averaged more than 2.0 percent and ranged up to 2.6 percent. The leaf samples were taken from even-aged white oak stands on 33 different sites in southeastern Ohio; stands ranged in age from 47 to 77 years and site index (tree height at age 50) varied from 47 to 77. In the same study Finn (1953) found no correlation between foliar calcium and site index or diameter growth, but did find foliar calcium content had a positive linear correlation with number of roots per square foot in the A horizon of the soil; at 0.50- and 0.75-percent foliar calcium there were 45 and 130 roots per square foot of A soil horizon, respectively. In this study, foliar potassium and phosphorus were unrelated to site index, diameter growth, stand density, or number of roots in the A soil horizon.

Comparative data are scarce, but it seems likely that tree species differ significantly in their relationships between growth and foliar chemical contents. For example, height of 18-year-old yellow-poplar in a plantation near the Dixon Springs Agricultural Center, Illinois, had significant positive correlation with foliar calcium, phosphorus, and magnesium as well as nitrogen; foliar potassium, however, was not significantly correlated with tree height (Gilmore et al. 1968). While evidently not related to height growth, foliar potassium content in yellow-poplar is related to frost damage in this species; the more foliar potassium the less leaf mortality occurs during killing frosts (White and Finn 1964).

FOLIAR ANALYSIS

Data on inorganic components of leaves of the pine-site hardwoods are absent or incomplete for some species and some elements. Tables 15-13 and 15-14 summarize some published data. Descriptions of foliage sampled by the cited investigators follow:

Reference	Foliage sample description
Auchmoody and Hammack (1975)	60-year-old, even-aged upland oak stand on Fernow mental Forest near Parsons, West Virginia; site index was 66. The stand had a tightly closed canopy averaging 217 stems per acre over 5.0 inches in dbh. Each value is the average for 10 trees from foliage collected throughout the crown in August.
Chandler (1941)	Closed stands of mixed species of second-growth hardwoods in central New York; dominant trees ranged from 30 to 70 years old. Foliage was caught in litter traps between October 18 and November 15.
Coile (1937)	Determinations made on leaves freshly fallen in the autumn from stands in the Piedmont region of North Carolina.
Johnson and Risser (1974)	The stand sampled was in central Oklahoma with trees up to 18 inches in diameter in a dense canopy of young trees and saplings; canopy height was 40 to 50 feet with about 1,052 trees per acre measuring larger than 1 inch dbh. Each value is the average for foliage clipped at about 20-foot height from 20 trees. Foliage was sampled throughout the growing season.
Lunt (1955)	Determinations made on freshly fallen leaves from uneven-aged trees in Connecticut.
MacHargue and Roy (1932)	Determinations for leaves of one tree of each species collected from several places in the crown at three times during the growing season. Trees sampled grew near the Kentucky Agricultural Experiment Station.
Metz (1952)	Determinations made on freshly fallen leaves in the South Carolina Piedmont. The stand had mixed hardwoods 1 to 150 years old.
Ovington (1956)	Each value is the average for foliage clipped from five trees of varying size in Bedgebury, England.
Woodwell et al. (1975)	Leaves were clipped from trees in early summer and again in autumn immediately prior to abscission; the study area was an oak-pine forest on Long Island, N.Y.
Young and Carpenter (1967)	Data are for foliage from 35-foot-high trees in Maine, based on regression analyses of trees of all heights.

TABLE 15-13.—*Foliar content of ash and six inorganic elements in hardwood species that grow on southern pine sites (ovendry weight basis)*

Species	Ash	Ca	K	Mg	Mn	P	N	Reference
	Percent	-mg/g-						
Ash, green	—	—	—	—	—	—	—	
Ash, white	—	23.7	5.4	2.7	—	1.6	5.9	Chandler (1941)
Elm, American	11.0	20.6	4.4	3.2	.1	1.5	7.7	MacHargue and Roy (1932); Chandler (1941)
Elm, winged	—	—	—	—	—	—	—	
Hackberry	—	—	—	—	—	—	—	
Hickory, sp.	—	27.8	—	6.2	—	—	6.2	Metz (1952)
Hickory, bitternut	—	34.1	4.4	—	—	1.2	6.8	Chandler (1941)
Hickory, shagbark	9.8	21.6	13.7	—	—	1.2	7.2	Lunt (1955)
Maple, red	6.0	9.0	—	—	—	—	5.0	Coile (1937)
Maple, red	5.3	12.1	4.0	2.6	—	1.1	4.2	Lunt (1955); Chandler (1941)
Maple, red	—	6.5	7.3	1.7	.7	2.2	15.1	Young and Carpenter (1967)
Maple, red	—	13.2	—	3.3	—	—	5.1	Metz (1952)
Oak, black	7.7	21.7	10.0	3.1	1.9	2.0	22.2	MacHargue and Roy (1932)
Oak, black	4.7	10.4	—	2.3	—	—	7.0	Metz (1952); Coile (1937)
Oak, blackjack	—	11.2	9.9	2.3	1.1	1.0	13.8	Johnson and Risser (1974)
Oak, blackjack	—	9.6	—	2.8	—	—	8.5	Metz (1952)
Oak, cherrybark	—	—	—	—	—	—	—	
Oak, chestnut	—	5.8	9.9	1.2	1.1	1.4	24.5	Auchmoody and Hammack (1975)
Oak, laurel	—	—	—	—	—	—	—	
Oak, northern red	—	5.7	10.8	1.3	1.8	1.2	25.2	Auchmoody and Hammack (1975)
Oak, northern red	4.7	6.7	7.9	2.0	5.4	1.7	28.7	Ovington (1956)
Oak, northern red	—	14.2	—	3.6	—	—	10.0	Metz (1952)
Oak, post	—	14.3	8.9	2.3	1.1	1.4	15.4	Johnson and Risser (1974)
Oak, post	—	9.7	—	2.2	—	—	8.0	Metz (1952)
Oak, scarlet	—	3.9	5.2	1.1	—	.5	7.9	Woodwell et al. (1975)
Oak, scarlet	—	4.4	7.6	1.0	1.6	1.2	22.2	Auchmoody and Hammack (1975)
Oak, shumard	—	—	—	—	—	—	—	
Oak, southern red	—	10.6	—	2.3	—	—	6.0	Metz (1952)
Oak, water	—	—	—	—	—	—	—	
Oak, white	—	5.2	7.9	1.0	1.1	1.5	25.3	Auchmoody and Hammack (1975)
Oak, white	7.7	16.9	—	3.0	—	—	9.2	Metz (1952); Coile (1937)
Oak, white	—	4.9	7.0	.9	—	.6	7.9	Woodwell et al. (1975)
Oak, white	5.9	13.6	5.2	2.4	—	1.3	5.4	Lunt (1955); Chandler (1941)

Table continued on next page.

TABLE 15-13.—*Foliar content of ash and six inorganic elements in hardwood species that grow on southern pine sites (ovendry weight basis)*—Continued

Species	Ash	Ca	K	Mg	Mn	P	N	Reference
	Percent	*mg/g*						
Sweetbay	—	—	—	—	—	—	—	
Sweetgum	8.2	19.7	6.0	4.3	.7	2.9	15.1	MacHargue and Roy (1932)
Sweetgum	6.9	13.0	—	4.7	—	—	4.9	Metz (1952); Coile (1937)
Tupelo, Black	—	—	—	—	—	—	—	
Yellow-poplar	10.7	25.6	9.5	4.5	.1	1.1	5.1	Chandler (1941); MacHargue and Roy (1932)
Yellow-poplar	6.6	26.1	—	7.2	—	—	5.3	Metz (1952); Coile (1937)

TABLE 15-14.—*Foliar content of five additional inorganic elements in nine southern hardwood species*

Species	Cu	Fe	Na	S	Zn	Reference
	mg/g					
Elm, American	0.007	0.68	1.1	0.7	0.02	MacHargue and Roy (1932)
Maple, red	.007	.11	—	—	.03	Young and Carpenter (1967)
Oak, black	.007	.25	.9	.04	.07	MacHargue and Roy (1932)
Oak, chestnut	—	.10	—	—	—	Auchmoody and Hammack (1975)
Oak, northern red	—	.10	—	—	—	Auchmoody and Hammack (1975)
Oak, northern red	—	.08	.1	—	—	Ovington (1956)
Oak, scarlet	—	.09	—	—	—	Auchmoody and Hammack (1975)
Oak, scarlet	—	.10	.05	2.6	—	Woodwell et al. (1975)
Oak, white	—	.09	—	—	—	Auchmoody and Hammack (1975)
Oak, white	—	.14	.04	3.2	—	Woodwell et al. 1975)
Sweetgum	.009	.20	.7	.1	.03	MacHargue and Roy (1932)
Yellow-poplar	.005	.28	.7	3.7	.03	MacHargue and Roy (1932)

VARIATION OF FOLIAR ANALYSIS WITHIN TREES

The chemical constituents of foliage vary between blade and petiole, and with position in the tree. Auchmoody (1974) found that nitrogen concentrations in leaf blades of yellow-poplar sampled near Parsons, West Virginia were 4 to 5 times higher than in petioles; phosphorus concentrations were nearly 3 times higher in blades than in petioles.

In a study of 60-year-old white, northern red, and chestnut oaks near Parsons, West Virginia, Auchmoody and Hammack (1975) concluded that concentrations of K, Ca, and Mg were generally higher in the lower than in the upper crown, while N, P, Mn, and Fe concentrations were unrelated to position. Direction of foliage orientation within the crown did not influence nutrient composition.

It is probable that harvesting will become increasingly intensive in southern forests. Knowledge of degree of harvest, coupled with knowledge of variation in nutrient contents among tree parts and forest components will help guide forest managers in planning nutrient replenishment regimes. On a percentage basis, leaves have higher proportions of N, P, K, Mg, and Mn than any other tree part or forest component (tables 15-15 and 15-16). It is perhaps more meaningful, however, to analyze the weight of these elements on a per-acre basis; when studied from this viewpoint, tree trunks and branches are found to contain the major reservoirs of nutrients, except for the soil (table 15-17).

TABLE 15-15.—*Concentrations of six mineral elements in various components of a post oak-blackjack oak forest in central Oklahoma* (Data from Johnson and Risser 1974)

Component	N	P	K	Ca	Mg	Mn
	mg/g					
Post oak						
Leaves	15.4	1.4	8.9	14.3	2.3	1.1
Current twigs	9.5	1.2	7.3	20.8	2.4	1.1
Smallest branches	8.9	.9	6.2	19.3	2.0	1.0
Large branches and trunks	2.1	.1	4.7	25.9	.7	.2
Bark	5.5	.2	4.6	90.2	1.1	.6
Wood	1.2	.1	4.7	9.0	.6	.1
Blackjack oak						
Leaves	13.8	.1	9.9	11.2	2.3	1.1
Current twigs	8.4	1.1	6.5	19.9	1.7	.6
Smallest branches	7.1	.7	5.8	20.1	1.3	.6
Large branches and trunks	1.9	.1	5.5	15.0	.8	.2
Bark	4.8	.2	5.4	37.2	.9	.7
Wood	.9	.0	5.6	7.4	.7	.1
Understory	7.3	.8	6.3	14.7	2.1	.4
Roots	4.3	.5	2.6	11.3	1.5	.6
Litterfall	7.9	.7	5.5	16.8	2.7	.9
Litter	5.4	.5	4.4	14.3	1.7	1.0
Soil, 0-15-cm depth	.4	.1	.1	.3	.1	.1
Soil, 30-45-cm depth	.2	.1	.1	.1	.1	.1

TABLE 15-16.—*Concentration of eight inorganic elements in tissues of scarlet oak and white oak (five-tree average, ovendry weight basis) from the Brookhaven oak-pine forest on Long Island, N. Y.* (Data from Woodwell et al. 1975)

Component	N	P	K	Ca	Mg	S	Fe	Na
	mg/g							
	SCARLET OAK							
Leaves in summer	7.90	0.49	5.15	3.88	1.07	2.55	0.10	0.05
Fruits	4.97	.94	6.60	6.60	.77	.83	.02	.13
Flowers	14.50	2.40	19.71	5.55	2.67	2.00	.22	.32
Current twigs	4.62	.72	2.53	5.15	2.76	.50	.03	.21
Branch live wood and bark	3.15	.27	2.07	5.20	.42	.33	.02	.11
Branch dead wood and bark	3.08	.07	.31	2.00	.15	.47	.16	.04
Stem outer bark	—	.35	.59	14.70	.39	.60	.26	.05
Stem inner bark	—	.57	2.60	18.70	.42	.44	.02	.05
Stem bark, mean	3.19	.42	1.47	13.40	.39	.43	.09	.04
Stem sapwood	1.00	.03	1.36	.52	.17	.26	.00	.13
Stem heartwood	1.40	.02	.60	.50	.06	.15	.01	.06
Root crown wood	2.16	.26	1.20	.69	.16	.32	.02	.10
Root wood	—	.41	2.43	.48	.62	.54	.02	.09
Root bark	—	.29	2.28	8.76	.57	.42	1.10	.05
Small whole roots	—	1.11	2.74	2.60	.54	.56	.33	.13
Roots, mean	3.42	1.11	2.74	2.60	.54	.56	.33	.13

Component	N	P	K	Ca	Mg	S	Fe	Na
	mg/g							
	WHITE OAK							
Leaves in summer	7.90	.63	7.04	4.91	.94	3.20	.14	.04
Fruits	6.43	1.02	7.77	1.83	.63	.97	.01	.05
Flowers	26.32	2.40	17.85	1.61	2.44	2.00	.12	.21
Current twigs	5.59	.79	3.95	6.44	.85	.70	.05	.06
Branch live wood and bark	2.80	.70	2.43	5.70	.66	.58	.07	.06
Branch dead wood and bark	4.32	.16	.19	3.40	.16	.60	.20	.04
Stem outer bark	—	.38	1.09	35.60	.45	.71	.22	.07
Stem inner bark	—	.49	2.40	28.10	.41	.42	.02	.05
Stem bark, mean	4.15	.47	1.82	25.10	.54	.53	.09	.05
Stem sapwood	1.53	.19	1.16	.85	.18	.20	.01	.04
Stem heartwood	1.88	.05	.73	1.02	.11	.14	.00	.05
Root crown wood	1.60	.21	1.65	.76	.14	.30	.01	.04
Root wood	—	2.30	1.83	1.33	1.09	.93	.03	.04
Root bark	—	.63	2.41	16.26	1.14	.83	.24	.09
Small whole roots	—	1.70	2.42	3.38	1.04	1.00	.09	.08
Root mean	2.00	1.70	2.42	3.38	1.04	1.00	.09	.08

TABLE 15-17.—*Distribution of biomass weight per acre by tree component and the weight per acre of six organic elements in a post oak-blackjack oak stand in central Oklahoma*. (Data from Johnson and Risser 1974)[1]

Component	Total component weight (ovendry)	N	P	K	Ca	Mg	Mn
	Pounds/acre						
Leaves[2]	4,278	36.6	4.6	25.5	72.7	8.2	5.4
Current twigs[2]	298	6.7	.9	5.9	3.8	1.7	.3
Branches with bark	57,629	538.1	52.7	395.2	997.1	110.5	55.9
Stemwood and bark	97,740	201.5	7.2	476.4	2,278.8	73.4	18.0
Roots[3]	34,811	150.8	17.9	91.8	391.7	50.3	20.5
Understory trees, above-ground[4]	1,259	9.1	1.0	7.3	18.9	2.8	.5
Dead wood	12,773	13.4	.6	65.4	104.8	8.8	.8
Litter[5]	9,611	76.7	5.6	54.9	192.4	21.9	9.2
Total	218,369	1,032.9	90.5	1,122.4	4,060.2	277.6	110.6
soil[6]	—	8,560.9	2,420.7	2,651.0	7,779.9	4,689.7	2,867.0

[1] The area sampled had trees up to 18 inches in dbh in a dense canopy of young trees and saplings; canopy height was 40 to 50 feet high with about 1,052 trees per acre measuring larger than 1 inch in dbh.

[2] Clipped from trees April through November.

[3] From soil samples taken with a post-hole digger.

[4] All plants less than 1 inch in dbh.

[5] Collected to mineral soil.

[6] Sampled to 18-inch depth.

SEASONAL VARIATION OF FOLIAR ANALYSIS

The nutrient content of hardwood leaves varies appreciably during the year because of leaching of nutrients by rainfall, transport within the plant, and changes in the structure of leaves at maturity. The pattern of change varies with the element, but young leaves of deciduous trees are usually richer in N, P, and K than mature leaves; content of Ca generally increases until abscission (Woodwell 1974).

Such variation of nutrient content in foliage is important to forest managers contemplating foliage harvest, as the harvest might be timed to minimize nutrient drain. Data on southern hardwoods are scarce, but some information is available on yellow-poplar, pignut hickory, and white, scarlet, and southern red oaks.

In Smalley's study[6] of 10-year-old planted yellow-poplars, about 2½ inches in dbh, on the Cumberland Plateau in Tennessee, dry leaf weight per unit leaf area increased about 20 percent during the growing season; moisture content (percent of ovendry weight) decreased after an early July maximum. Seasonal trends for each element were similar whether foliar nutrient was expressed as concentration (percent of ovendry weight) or content (mg/cm^2) (fig. 15-15). Nitrogen concentration decreased during the season; N content remained constant through mid-August, then decreased. Phosphorus concentration and content was relatively stable, and concentration and content of K and Mg gradually increased. Calcium concentration and content increased rapidly in early summer, decreased in mid-September, and reached a seasonal high before leaf abscission.

From leaves of pignut hickory and southern red oak collected in late April, May, and July near Raleigh, N. C., Clark et al. (1970) found that P, K, Zn, Na, and Cu decreased in both species with leaf maturation; content of Ca, Al, and Fe increased. Changes in these elements were greater in hickory than in southern red oak. Total ash content did not change with maturation of hickory leaves, but increased 5 percent in oak leaves.

McVickar (1949) observed that in white oak leaves from various soil types in Illinois, percentage of Ca increased as the season advanced; Mg content remained fairly constant, and the content of K, P, and N decreased as the season advanced.

Woodwell (1974) clipped mid-crown scarlet oak and white oak leaves at six dates during a summer from an oak-pine forest on Long Island, N.Y.; he found that leaf weight per unit area (ovendry basis) increased by 30 and 50 percent respectively. N, P, and K content increased to a peak in mid- or late summer and declined abruptly just before abscission; concentrations of other elements tended to rise slowly throughout the growing season (fig. 15-16).

Content of inorganic elements in litter also varies with the passage of time. In an Illinois oak-hickory forest, Akhtar et al. (1976) placed freshly fallen leaves in baskets on mineral soil, covered them to prevent further litter additions, and analyzed them at 2-month intevals. Concentrations of N, P, and Ca increased with the passage of time, while K and Mg decreased. The following relationships express the concentration of five elements (ppm) in terms of t (months of exposure):

$$N = 9{,}716 + 298.1t \qquad R^2 = 0.88 \qquad (15\text{-}1)$$
$$P = 900 + 44.48t \qquad R^2 = .27 \qquad (15\text{-}2)$$
$$K = 1{,}852 - 48.56t \qquad R^2 = .88 \qquad (15\text{-}3)$$
$$Ca = 15{,}845 + 165.5t \qquad R^2 = .32 \qquad (15\text{-}4)$$
$$Mg = 1{,}349 - 2{,}904t \qquad R^2 = .84 \qquad (15\text{-}5)$$

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[6] Smalley, G. W. 1976. Seasonal variation in the nutrient composition of yellow-poplar leaves. 19 p. Paper presented at the Cent. Hardwood For. Conf. at South. Ill. Univ., Carbondale. Oct. 17-19.

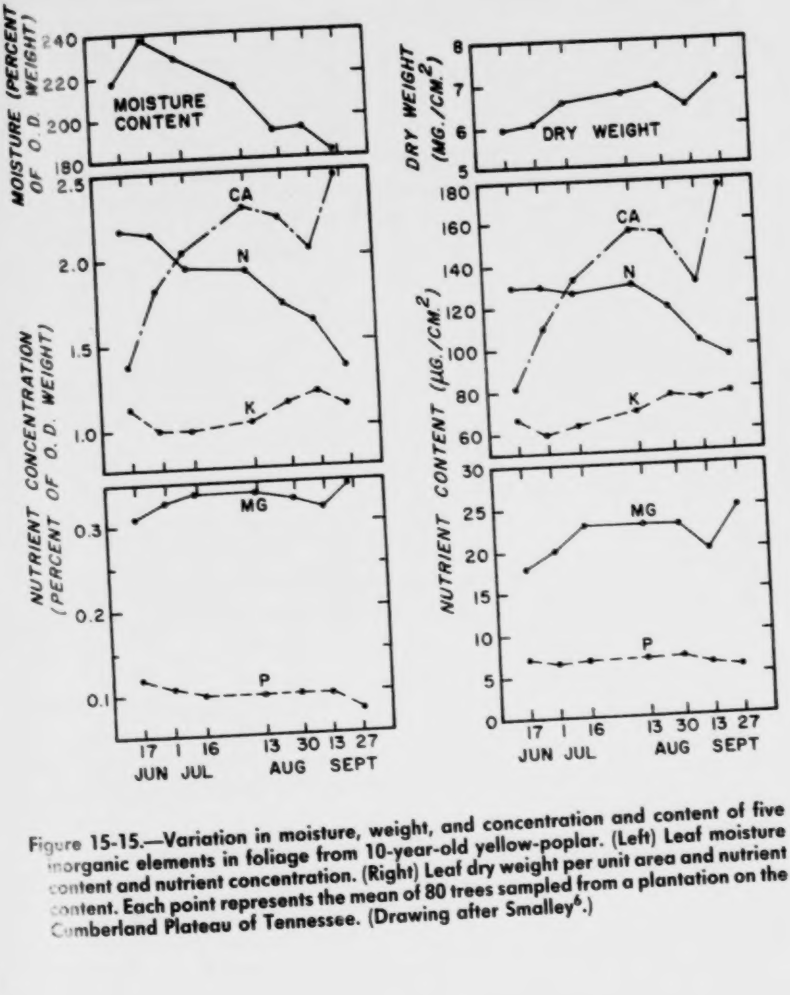

Figure 15-15.—Variation in moisture, weight, and concentration and content of five inorganic elements in foliage from 10-year-old yellow-poplar. (Left) Leaf moisture content and nutrient concentration. (Right) Leaf dry weight per unit area and nutrient content. Each point represents the mean of 80 trees sampled from a plantation on the Cumberland Plateau of Tennessee. (Drawing after Smalley[6].)

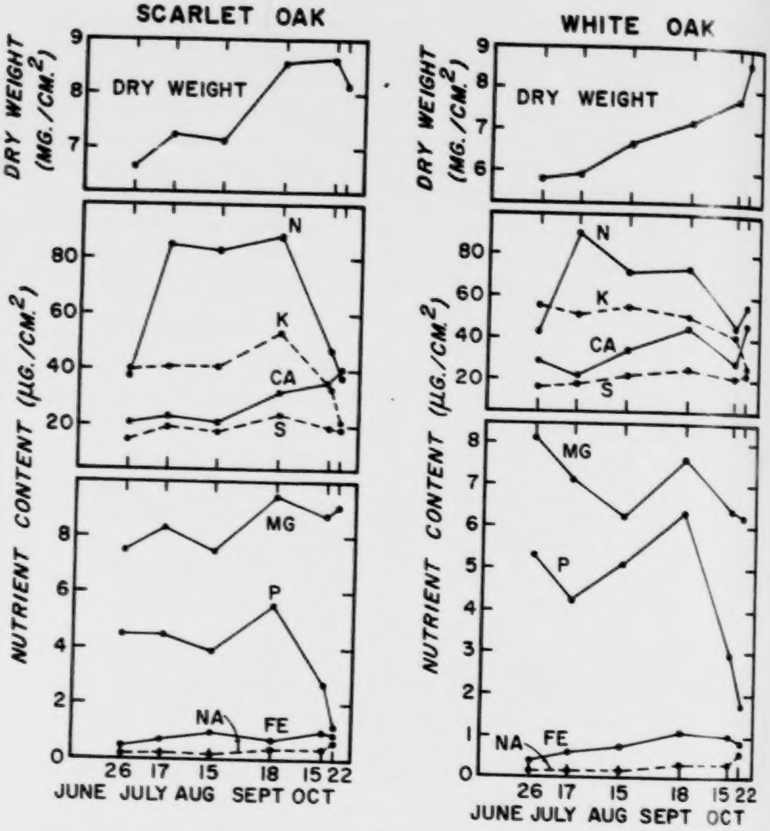

Figure 15-16.—Variation in dry weight and content of eight nutrients in leaves of two hardwood species during summer. (Left) Scarlet oak. (Right) White oak. (Drawing after Woodwell 1974.)

NUTRIENTS PER ACRE

Managers contemplating replenishment of nutrients following harvest of live foliage or litter must be concerned with nutrient drain on a per-acre basis. Some data on a post oak-blackjack oak forest are abstracted from table 15-17 as follows:

Element	Leaves	Litter
	Pounds/acre	
N	36.6	76.7
P	4.6	5.6
K	25.5	54.9
Ca	72.7	192.4
Mg	8.2	21.9
Mn	5.4	9.2

Metz (1952) studied three hardwood stands in Union County, S.C., and concluded that litter fall annually contributed the following amounts of three nutrients per acre:

Element	Pounds per acre
N	26
Ca	88
Mg	21

Nitrogen is accumulated in the litter on the forest floor. Metz (1954) measured the nitrogen content of litter on the forest floor under the tree stands just mentioned, with results as follows:

Stand description	Nitrogen in litter on forest floor
	Pounds/acre
Predominantly yellow-poplar with trees up to 45 years old	145
Mostly hickory 150 years old	85
Mostly oak	134

WAX CONTENT OF LEAVES

Leaves of southern hardwood trees contain small amounts of wax—probably 2 percent or less depending on species and method of analysis (table 15-18).

pH OF LEAVES

The pH levels of macerated leaves of eight pine-site hardwoods have been determined to range from 3.8 to 6.0 depending on species and season of the year (table 15-19).

TABLE 15-18.—*Content of ether extractable waxes in leaves of eight southern hardwoods*. (Data from Brady[1])

Species	Wax content[2]
	Percent of green (fresh) leaf weight
Maple, red	3.4
Sweetbay	2.0
Ash, green	1.5
Sweetgum	1.4
Oak, blackjack	1.1
Oak, water	1.1
Oak, southern red	1.0
Elm, winged	.9

[1] Brady, H. A. 1971. Foliar characteristics of six species of hardwoods. Final Reports FS-SO-1102-4.35 and 4.49. U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Alexandria, La. 102 p. and 105 p.

[2] Each value is based on data from nine saplings (up to 4 inches in dbh) sampled from the Kisatchie National Forest in Louisiana. The values tabulated resulted from six 2-hour extractions; it is likely that soluble materials, in addition to waxes from the cuticle, were extracted.

TABLE 15-19.—*pH of homogenized leaves from eight species of hardwoods*. (Data from Brady[1].)

Species	Early summer[2]	Late summer[2]
Ash, green[3]	6.0	5.8
Elm, winged[3]	5.8	5.7
Maple, red[4]	3.9	4.2
Oak, blackjack[4]	4.5	4.9
Oak, southern red[4]	4.4	4.8
Oak, water[3]	4.4	4.6
Sweetbay[3]	5.5	5.4
Sweetgum[4]	3.8	4.2

[1] Brady, H. A. 1971. Foliar characteristics of six species of hardwoods. Final Reports FS-SO-1102-4.35 and 4.49. U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., Alexandria, La. 102 p. and 105 p.

[2] Each value is based on data from nine saplings sampled from the Kisatchie National Forest in Louisiana.

[3] Early summer sample taken April 25 through June 25; late summer sample taken July 25 and August 25.

[4] Early summer sample taken May 16 through July 19; late summer sample taken August 3 through September 13.

15-4 FOLIAGE PHYSICAL AND MECHANICAL PROPERTIES

Manufacturers contemplating use of leaves require knowledge of their physical and mechanical properties as well as their chemical composition. Moisture content, heat of combustion, strength, and color are among the properties of interest.

MOISTURE CONTENT OF LEAVES

The moisture content of leaves is related to their function during **transpiration,** i.e., the process by which water is taken from the soil by trees and evaporated—first from the wet cells of leaves into intercellular spaces, and then by diffusion of water vapor from the intercellular spaces to the outside air. The amounts of water taken up by trees and lost to the atmosphere by transpiration are very large. Southern forests are estimated to lose through transpiration as much as 8,000 gallons of water per acre per day (Kozlowski and Davies 1975).

During transpiration, leaves dehydrate during the day and rehydrate at night. Chaney and Kozlowski (1969a) observed that the leaves of northern red oak in Wisconsin have about 150-percent moisture content (ovendry weight basis) at 5 a.m. in the morning, but only 130-percent at 2 p.m. (fig. 15-17).

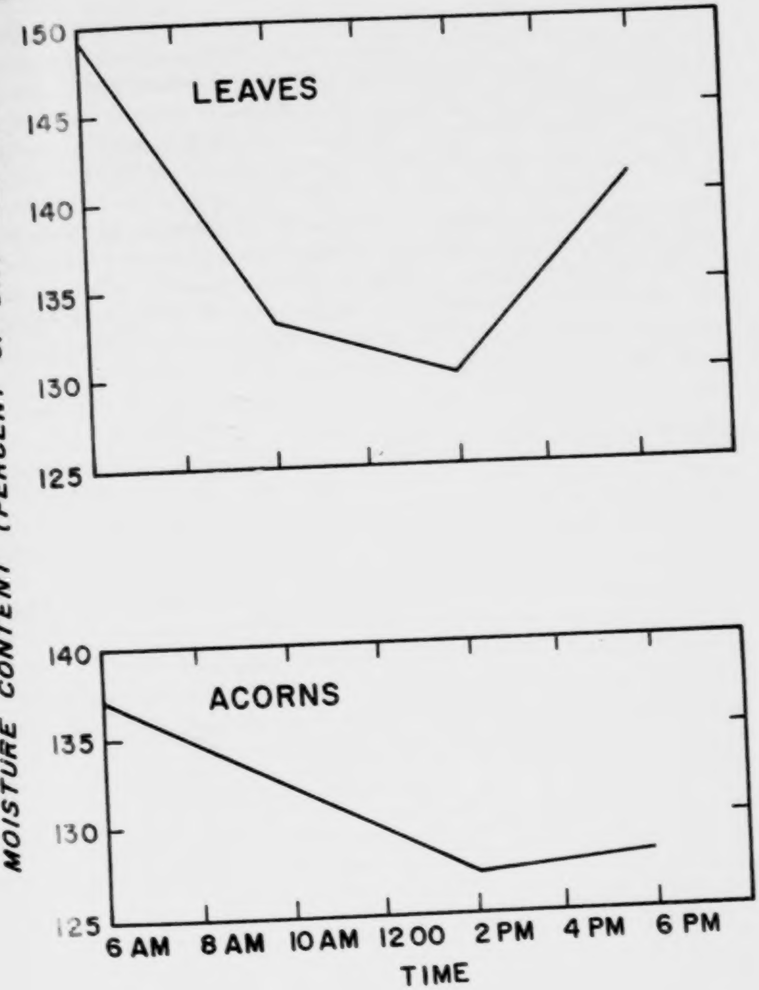

Figure 15-17.—Diurnal variation in moisture contents of leaves and acorns of northern red oak during summer in Wisconsin. (Drawing after Chaney and Kozlowski 1969a).

Seasonal variation in foliage of southern hardwoods is also substantial; leaf moisture contents are maximum (250- to 320-percent of dry weight) early in the growing season and minimum (120 to 180 percent) in mature leaves just prior to abscission in autumn. Data on yellow-poplar are shown in figure 15-15 and for sycamore (*Platanus occidentalis* L.) in figure 8-3. Clark et al. (1970) reported that the water content of pignut hickory leaves in North Carolina decreased by about 11 percentage points in the first month of the growing season, and that of southern red oak leaves decreased by about 22 percentage points during the same period; hickory leaves decreased an additional 9 percentage points in the next 2 months. Leaves of northern red oak in Wisconsin were observed by Kozlowski and Clausen (1965) to have about 300 percent moisture content (ovendry weight basis) at the end of May, about 150 percent in mid-July, and only 125 percent in early September.

MOISTURE CONTENT OF LITTER

In a yellow-poplar, hickory, and scarlet oak stand near Franklin, N.C., Helvey (1964) found maximum moisture content of litter on the forest floor was about 215 percent of ovendry weight. About 1 inch of throughfall of rain was required to wet the litter to this maximum. Litter dries rapidly after a rainfall, especially in the dormant season, its moisture content being reduced by a half or two-thirds within 4 days after heavy rainstorms (fig. 15-18 and Blow 1955).

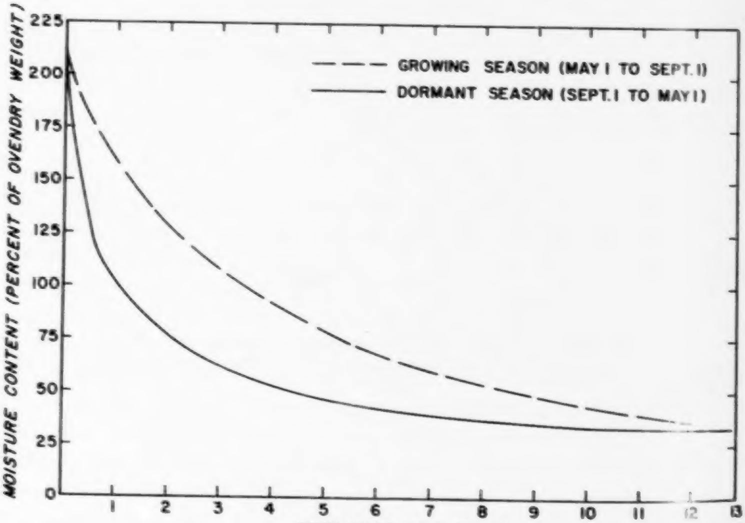

Figure 15-18.—The relationship between hardwood litter moisture content and time since wetting for dormant and growing seasons. (Drawing after Helvey 1964).

Process engineers are frequently concerned with the drying rate and equilibrium moisture contents of their raw materials. Dunlap (1932) soaked leaves from the forest floor in water overnight and placed them between screens exposed to air of 30-percent relative humidity at 80°F flowing at 5 miles per hour. They dried from 500-percent moisture content (ovendry weight basis) to 100-percent moisture content in 20 minutes, and to 30-percent moisture content in 60 minutes.

When dry, detatched hardwood leaves are exposed to air of increasing relative humidity (adsorption) and then to air of decreasing relative humidity (desorption), plots of the equilibrium moisture contents attained exhibit hysteresis loops typical of plant material. Thus southern red oak leaves reach 8-percent moisture content when increasing relative humidity of air reaches about 35 percent, but do not dry below 8-percent until humidity declines to about 18 percent (fig. 15-19). In contrast to red oak, mockernut hickory leaves, under increasing humidity, reach 8-percent moisture content at about 15-percent relative humidity, and return to this level when relative humidity declines to about 10 percent. At any relative humidity, southern hardwood leaves have significantly higher equilibrium moisture contents than stemwood (fig. 8-9).

HEAT OF COMBUSTION

The southern forest industry is developing methods for harvesting cull trees complete with branches and foliage for use as fuel to generate steam. The heat of combustion of foliage is therefore of interest. Following are some heat values of ovendry leaves and litter determined in an oxygen bomb calorimeter, and ash contents:

Foliage description	Heat of combustion	Ash content	Reference
	Btu/pound	*Percent*	
Freshly fallen leaves			
Red maple	7,969	6.2	Reiners and Reiners (1970)
White oak	8,044	5.6	Reiners and Reiners (1970)
Winged elm	8,110	8.5	Hough (1969)
Post oak	8,786	2.4	Hough (1969)
Mixed upland hardwoods	8,020	7.2	Hough (1969)
Upper litter, scrub oak (Georgia)	8,408	6.0	Hough (1969)
Lower litter, scrub oak (Georgia)	7,783	21.9	Hough (1969)
Post oak litter (Texas)	6,936	19.9	Hough (1969)

STRENGTH

Except for the veins, leaves from hardwood trees have no tissues that contribute significantly to tensile, tear, or burst strength. Strength values of leaf blades are therefore so low (table 15-20) that it is unlikely that they can be utilized in flakeboards or particleboards; even the central veins, which have modest strength (2,500 to 10,000 psi in tension), are not likely candidates for fiber products because they constitute such a minor portion of tree weight.

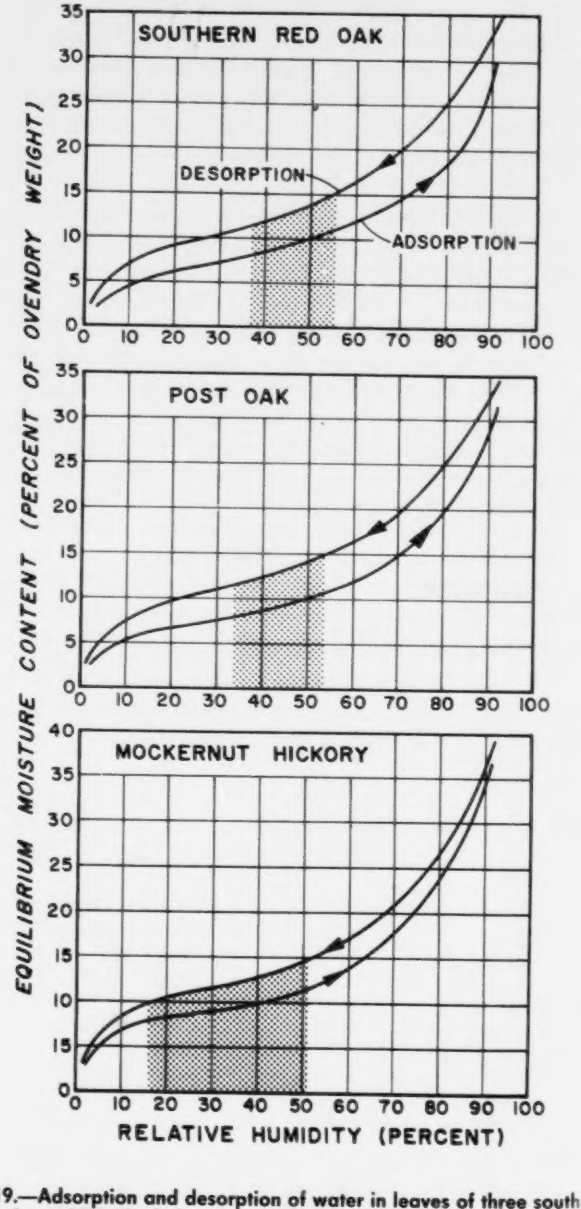

Figure 15-19.—Adsorption and desorption of water in leaves of three southern hardwood species at 80°F. Shaded areas depict range of relative humidities in which both adsorption and desorption equilibrium moisture contents are between 8 and 15 percent. (Drawing after Blackmarr 1971.)

COLORATION[7]

One of the major values of hardwoods growing on southern pine sites is the esthetically pleasing panorama provided by autumn coloration in their leaves. What produces the yellows, reds, and browns typical of hardwood foliage in the fall? Frost is not the cause; in fact, early frost greatly reduces the abundance and brilliance of autumn leaf colors by curtailing pigment development.

TABLE 15-20.—*Strength of midrib veins in tension, and burst strength of leaf blades from nine pine-site hardwoods*[1]

Species	Midrib vein, tension			Leaf blade
	Breaking load	Ultimate strength	Modulus of elasticity	Burst strength[2]
	Pounds	................*Psi*................		
Ash, white	4.9	6,300	350,000	2.0
Elm, American	4.8	6,500	340,000	2.5
Hickory, mockernut	4.8[3]	5,900	300,000	1.6
Oak, southern red	5.9	7,400	410,000	3.7
Oak, post	11.9	9,700	430,000	2.0
Oak, white	12.0	10,000	430,000	2.6
Sweetbay	4.7	5,400	290,000	1.9
Sweetgum	1.4[4]	2,500	280,000	1.8
Tupelo, black	5.6	7,900	390,000	1.6

[1] Leaf portions equilibrated at 70°F and 50 percent relative humidity. Each value is an average of data obtained from two leaves clipped in midsummer from mid-crown of each of three trees in Louisiana.

[2] Leaf entire, except for compound leaves where individual leaflets were tested.

[3] Midrib tensile specimens obtained from leaflet blades.

[4] Midrib tensile specimen obtained from vein nearest center of leaf.

Autumn foliage colors result from seasonal chemical reactions within leaf cells. All autumn hues are blends from three primary pigments, rich yellow carotene, paler yellow xanthophyll, and red to purplish anthocyanin. Carotene and xanthophyll are stable, and abundant in chloroplasts throughout the growing season, but are normally masked by an outer layer of green chlorophyll. The latter, being chemically unstable, is depleted when cold nights and reduced sunlight in the fall reduce the rate at which it is synthesized, thus revealing the underlying yellows. The red anthocyanins are produced from sugars under slanting autumn sunlight and temperatures between 45°F and freezing. Water soluble and not confined to chloroplasts, they appear in outer cell layers and tend to hide other colors.

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[7] Text under this heading is condensed from Stanton (1976).

The most vivid colors appear in dry autumns after warm summers if enough early autumn rains prevent premature leaf fall. Long periods of wet fall weather produce a rather drab coloration. Drought favors anthocyanin formation by reducing tree metabolism and nitrate absorption. Among pine-site hardwoods, color combinations are most vivid in red maple, black tupelo, sweetgum, northern red oak, and scarlet oak. Yellow-poplar and the hickories produce few anthocyanins and usually display a golden color.

Progress of autumn coloration among trees of a species may vary according to seed source. Gabriel (1958) found that in Shumard oak grown at Philadelphia, Pennsylvania, fall coloration was delayed in trees from southern seed; such trees continued growth and retained green leaves later in the season than did those from more northerly seed sources. Leaf coloration in four lots of seedlings observed on November 10-14 of their second year was as follows:

Seed source	All green	Green combined with red and brown	All red, brown, or with dropped leaves
	Percent of trees		
Richland Co., Ill.	1	28	71
Knox Co., Tenn.	7	66	27
Tallahatchie Co., Miss.	10	78	12
Alucha Co., Fla.	77	15	8

15-5 FOLIAGE AS FOOD

Leaves of pine-site hardwoods can provide protein-rich liquids for animal or human consumption, dried ground meal to supplement animal fodder, pigments used in poultry and egg production, and browse for deer and other wildlife.

CAROTENOIDS[8]

Associated with chlorophylls in foliage, the carotenoids are labile, oxidizable, highly unsaturated yellow pigments. These include α, β, and γ-carotene, neoxanthin, flavoxanthin, and lutein and its eposide, zeaxanthin. The last two have promise as pigments for poultry and egg production; in the past, they have been isolated from alfalfa and marigolds, or they were made by expensive chemical synthesis. The long term future for tree foliage, as a source of these pigments appears promising.

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[8] Text under this heading is condensed from: Barton, G. M. 1978. Chemicals from trees, outlook for the future. Presented at Eighth World For. Cong., Jakarta, Indonesia, Oct. 16-28. 20 p.

Caratenoids have additional nutritional value because of the ease with which β-carotene can be hydrolyzed to vitamin A. Foliage of southern hardwoods can also be an important source of vitamins C, E, and K, provitamin D, and riboflavin.

LEAF PROTEIN[8]

Trees, like other green plants, require nitrogen for production of protein in order to photosynthesize carbon dioxide into sugars. Although coniferous foliage contains only 7 to 8 percent protein, as much as 19.5 percent has been reported for some deciduous species (Dickson and Larson 1977). This exceeds the 18 percent average content of alfalfa, and suggests that some hardwood leaves could provide protein for animal and human consumption. Although protein-rich juice can be liberated from leaves by simple mechanical presses, there are difficulties in removing tannins and phenolic substances from them (Pirie 1975).

MUKA

Problems with leaf juices have prompted Soviet animal nutritionists to dry and grind both deciduous and coniferous foliage for use as animal fodder supplement (**muka**).

Keays (1976) noted that muka provides a source of biologically active components, vitamins, and trace elements (table 15-21), as well as nutrients, and results in healthier, more productive, disease-resistant livestock. Muka from birch is considered a satisfactory replacement for an equivalent weight of alfalfa or clover meal, but its low protein content—about half that of alfalfa meal (table 15-21)—may require a protein supplement. As the amount of muka in animal rations increases above an optimum level, productivity and weight increase falls off; somewhere between 20 and 30 percent of the total ration, the point of rejection is reached. Muka is used primarily in poultry feeds, and less extensively feeds for cattle.

In a study of deer browse in southern forests, Short et al. (1975) found that twigs are most succulent, nutritious, and digestible during spring while growing rapidly. When mature, usually by early summer, they were less digestible and contained more fiber (table 15-22). In mature twigs, quality and digestibility decline with distance from twig tip. Leaves of deciduous species usually lose nutrient quality and digestibility after abscission. Browse leaves from evergreen species retain their good forage quality and digestibility throughout the year.

TABLE 15-21.—*Comparison between alfalfa meal and typical birch (Betula sp.) muka prepared from commercial foliage*[1] (Data from Keays 1976)

Components	Birch muka	Alfalfa meal
Carotene, mg/kg	380	172
Protein, percent	8.0	18.3
Fats, percent	8.2	3.2
Cellulose, percent	18	26
Nitrogen-free extractives, percent	57	42
Ash, percent	4.2	9.6
Riboflavan, mg/kg	4	13
Calcium, percent	0.8	1.1
Phosphorus, percent	0.3	0.3
Potassium, percent	0.7	1.3
Magnesium, percent	0.3	0.2
Iron, mg/kg	101	212
Manganese, mg/kg	30	29
Copper, mg/kg	8	10
Zinc, mg/kg	121	16
Cobalt, mg/kg	90	360

[1] Commercial foliage from hardwood trees is defined as all leaves, twigs, shoots, and branches up to 0.24 inch in diameter.

WILDLIFE FOOD

Leaves and twigs of many of the pine-site hardwoods provide food for wildlife-principally deer. A review of the literature on the subject is beyond the scope of this text, but Halls (*in press*) has edited a book which collates information pertinent to the white-tailed deer. Some other references that should be useful to readers interested in the subject follow:

- Forage composition and digestibility
  - Segelquist et al. (1972)
  - Short (1966, 1971)
  - Short and Reagor (1970)
  - Short et al. (1975)
- Improvement of supplies of food for wildlife
  - Blair and Brunett (1980)
  - Gysel et al. (1972)
  - Halls (1970ab)
  - Halls and Ripley (1961)
  - Halls et al. (1970).
  - Healy (1971)
  - Knierim et al. (1971)
  - Schuster and Halls (1962)
  - Stransky and Halls (1967)
- Inventory and habitat capacity
  - Biswell and Hoover (1945)
  - Blair (1971)
  - Crawford (1976)
  - Crawford et al. (1975)
  - Cushwa et al. (1970)
  - Gill et al. (1975)
  - Halls (1978)
  - Halls and Alcaniz (1970)
  - Halls and Homesley (1966)
  - Harlow et al. (1975)
  - Harlow et al. (1966)
  - Loomis (1977)
  - Maddocks (1976)
  - Pearson and Sternitzke (1976)
  - Segelquist and Green (1968)
  - Segelquist and Pennington (1968)
  - Wolters and Wilhite (1974)
  - Wolters et al. (1977)

TABLE 15-22.—*Protein, fiber, and phosphorus content and digestibility of twigs and leaves of four southern hardwoods sampled in east Texas during four seasons* (Data from Short et al. 1975)[1]

Species and season	Dry matter	Crude protein[2]	Crude fiber[2]	Phosphorus[2]	Digestibility[3]
	Percent of green weight	*Percent of ovendry weight*			
FOUR-INCH-LONG TERMINAL TWIGS					
Water oak					
Spring	26.7	10.4	33.4	0.24	55.3
Summer	56.5	4.2	41.7	.13	38.6
Autumn	56.6	4.9	41.5	.09	35.3
Winter	58.5	5.9	41.0	.09	40.2
Winged elm					
Spring	30.8	18.2	25.3	.35	78.3
Summer	59.0	5.4	41.9	.10	44.9
Autumn	61.1	5.8	38.0	.11	42.0
Winter	60.8	7.7	39.6	.08	47.0
Sweetgum					
Spring	19.6	14.5	14.6	.39	77.6
Summer	38.8	3.7	27.5	.08	54.2
Autumn	43.0	5.6	26.4	.10	56.3
Winter	43.0	6.6	34.1	.10	51.3
Black tupelo					
Spring	15.4	10.0	20.5	.22	83.1
Summer	48.3	3.8	35.2	.07	43.1
Autumn	54.9	4.9	36.5	.06	38.6
Winter	47.2	5.5	38.7	.12	44.4
LEAVES					
Water oak					
Spring	29.9	19.1	16.7	.32	59.0
Summer	52.3	10.3	25.9	.09	41.2
Autumn	57.5	12.2	27.1	.12	40.3
Winter	57.4	10.5	24.6	.11	50.9
Winged elm					
Spring	34.5	27.6	11.5	.46	89.7
Summer	55.2	11.2	20.6	.12	54.4
Autumn	55.0	8.8	20.7	.12	51.4
Winter	[4]	7.3	25.8	.07	26.6
Sweetgum					
Spring	25.8	16.9	9.4	.30	71.5
Summer	35.6	9.8	11.2	.11	54.2
Autumn	37.9	9.9	9.4	.13	61.7
Winter	[4]	5.3	17.3	.06	39.1
Black tupelo					
Spring	20.3	15.1	10.8	.22	80.9
Summer	39.4	8.8	14.8	.10	54.7
Autumn	41.4	6.8	17.9	.07	56.7
Winter	[4]	6.4	22.8	.11	56.7

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[1] Samples were taken within 5 feet of ground level. Values tabulated are averages for a sample that was a composite from several trees.

[2] Assayed by methods of Horowitz (1965).

[3] Determined with ruminally cannulated goats.

[4] No dry matter measurements were made on winter leaves picked from the ground.

15-6 OTHER USES OF FOLIAGE

Foliage of southern hardwoods has some uses in addition to muka for domestic animals and browse for wildlife. Some of the uses are more potential than actual, and some apparent avenues for utilization show little promise. For example, Keays (1975) noted that the yield of pulp from foliage is extremely low (10 percent or less by weight of the ovendry foliage); foliage pulp that survives a kraft cook is extremely weak and would probably pose a problem in increased dirt count.

Chow[9] concluded that hardwood leaves are an unsatisfactory material from which to make particleboard. In his experiment he spread dry oak leaves (*Quercus* sp.) with urea formaldehyde resin and pressed boards to a density of 49 pounds per cubic foot. Bulk density of the dry leaves (not hammermilled) before adhesive application was only 3.0 pounds per cubic foot; when hammermilled, bulk density of the adhesive-free foliage was 4.8 pounds per cubic foot. Completed boards had properties as follows:

Property	Value
Modulus of rupture (psi)	600
Modulus of elasticity (psi)	60,000
Internal bond strength (psi)	15
Screw holding ability (pounds)	30
Water absorption after 2 hours of water soak (percent)	15
Thickness swell after 2 hours of water soak (percent)	9

Other foliage products such as fillers and extenders for adhesives, and essential oils and specialty chemicals, show more promise.

ADHESIVE EXTENDER

Chow (1977) and Barton et al. (1978) reported that western coniferous technical foliage—if dried at 105°C to less than 10-percent moisture content, ground in a Pallman ring grinder, and brought to neutral pH—could successfully replace wheat flour as an adhesive extender and bark as an adhesive filler in phenol-formaldehyde glues for plywood and particleboard.

No comparable research has been done with technical foliage of southern hardwoods, but the idea appears interesting since the supply of conventional fillers and extenders such as wheat flour, corn cobs, walnut shells, and bark is becoming uncertain, and their prices are increasing.

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[9] Chow, P. 1974. Dry formed composite board from selected agricultural fiber residues. Doc. No. 110, 8 p. Paper presented at World Consultation on Wood Based Panels, Food and Agric. Organ. of the United Nations.

ESSENTIAL OIL[10]

Steam distillation of foliage for essential oils is one of the oldest chemical processes known and has been widely practiced for many years in Europe, North America, and the Soviet Union. Essential oils can be simply prepared from a wide variety of species by passing steam through finely divided leaves and twigs, collecting the distillate and separating the oil from the water. The equipment is not complex and its cost relatively low, but the high labor costs to collect leaves and twigs, and low yields of oil (approximately 1 percent) have precluded large-scale, industrial development over the centuries. Innumerable (and undocumentable) efforts have been made the world over to recover essential oils from tree foliage. In general, these efforts have been small scale and short lived. Processing has been crude, the product highly variable in quality, and production low and sporatic; as far as is known, little or no effort has been made to utilize the residue. The literature contains no data on foliage of hardwoods growing on southern pine sites.

Recovery and use of foliage essential oils is most developed in the Soviet Union where it is second only to muka manufacture in the field of foliage utilization. Plants are widely scattered throughout the USSR, using foliage of a number of species, particularly *Abies*; conversion from batch to continuous systems is underway.

Essential oils are used in perfumes, bath additives, and air fresheners because of their fragrance and medicinal properties. For their physiological effects, they are also used in medicines for treatment of internal disorders (Keays 1976).

Readers interested in the enumeration and structure of foliage chemicals will find Barton's (1976,[11]) reviews useful.

CHLOROPHYLL-CAROTENE PASTE[12]

Chlorophyll-carotene paste is obtained by the extraction of foliage with petroleum ether; 2,000 pounds of green foliage yields about 80 pounds of paste. Constituents of the paste which are of greatest interest include chlorophyll, carotene (and other carotenoids), vitamins A and E, sterols, and other biologically active substances. In the Soviet Union, 10 plants produce a total of about 550,000 pounds of chlorophyll-carotene paste per year used in burn ointments, toothpastes, bath additives, soaps, lotions, and perfumes. Veterinarians use it to promote faster growth, greater stamina, and improved health of poultry and cattle.

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[10] Text under this heading is based on Keays and Barton (1975).

[11] Barton, G. M. 1978. Chemicals from trees, outlook for the future. Paper presented at Eighth World For. Congr., Jakarta, Indonesia, Oct. 16-28. 20 p.

[12] Text under this heading is condensed from Keays and Barton (1975).

Chlorophyll-carotene paste can be further processed with sodium hydroxide to yield sodium chlorophyll—a medicine used as a bacteriacide, in treatment of skin diseases and stomach and nervous disorders, and as a blood restorative; it is also used in cosmetics for coloring, and as a deodorant.

Another product obtainable during production of sodium chlorophyll is provitamin concentrate; 2,000 pounds of green foliage yield about 10 pounds of concentrate. It is used in animal nutrition, in cosmetics, and in perfume for its fragrance.

15-7 SEEDS

The seeds of hardwoods growing on southern pine sites have—in addition to their use for tree regeneration—great value as food for wildlife. This food value is substantial despite the small percentage of tree weight accounted for by mature seeds. Whittaker et al. (1963), in a study of dominant and codominant trees in eastern Tennessee, found that 10 yellow-poplars averaging 75 years old and 34 inches in diameter had fruit amounting to 0.3 percent of the total weight (ovendry basis) of above-ground tree portions; a 10-tree sample of 96-year-old white oak 40.8 inches in diameter produced fruit amounting to only 0.02 percent of their total above-ground weight.

Among the pine-site hardwoods, seeds of oaks, hickories, and black tupelo are important foods for squirrels and turkeys. Acorns are a preferred food for deer. Quail feed on seeds of oaks, ashes, black tupelo, red maple, and sweetbay. Raccoons and opossum also use the seeds of pine-site hardwoods for food (Bateman 1959ab). Acorns are eaten by ducks, crows, bluejays, and woodpeckers, and mice and rats consume part of each acorn crop (Reid and Goodrum 1957). When pine and hardwoods are harvested to make way for succeeding tree plantations, the ensuing brushy growth contains shrub species that provide seed favored by songbirds (Stransky et al. 1976) and quail. Unfenced hogs are domestic acorn users and therefore compete with wildlife for this food source.

A text on utilization therefore considers tree seed from a somewhat different perspective than that emphasized by nurserymen. Here, data on seed physical description, seed yield per tree and per acre, animal food preferences, and nutrient content are important.

Seasonal timing of flowering and seed production of each species is briefly described in chapter 3.

SEED DESCRIPTION

The seed of a pine-site hardwood (fig. 15-20) consists of a miniature undeveloped plant **embryo**) surrounded by a quantity of stored food tissue (**endosperm**) available for its early nourishment, and a protective **seed coat.** The embryo consists of two seed leaves (**cotyledons**) and a somewhat elongated axis from which the cotyledons grow as lateral appendages. The portion of the axis above the point of attachment of the cotyledons is called the **epicotyl,** that below the attachment the **hypocotyl,** the lower end of which is the **root-primordium** or **radicle.** A **fruit** is a matured ovary, and a **seed** is a matured ovule, which is produced inside the fruit. As an ovary ripens into a fruit, its wall (**pericarp**) may thicken and become differentiated into three rather distinct layers of tissues, of which the **exocarp** is outermost, the **mesocarp** is central, and the **endocarp** is innermost (Fuller and Tippo 1949).

Among pine-site hardwoods, the oaks and hickories have heavy seeds; species with light seeds include the ashes, elms, red maple, sweetgum, and yellow-poplar. More descriptively, fruits of pine-site hardwoods can be classified as drupes (hackberry, sugarberry, and black tupelo), nuts (oaks and hickories), samaras (ashes, elms, and maples), multiple capsules (sweetgum), and aggregates (sweetbay).

A **drupe** is a fleshy or pulpy fruit in which the inner ovary wall (endocarp) is hard and strong, enclosing a seed (figs. 3-54 and 3-57). **Nuts** are hard, indehiscent, one-celled, and one-seeded fruits; they are commonly referred to as **hard mast** (figs. 3-37 through 3-40, and 3-42 through 3-53). A **samara** is an indehiscent winged fruit (figs. 3-33 through 3-36, and 3-41). A **capsule** is a dry dehiscent fruit composed of more than one carpel; in sweetgum the capsules are fused at the base into a round prickly head, each capsule with one or two seeds (fig. 3-56). An **aggregate** is a fruit developing from a cluster of simple ovaries of a single flower (fig. 3-55).

Seed sizes and weights vary greatly among species; for example, only about 36 mockernut hickory seeds are required to total 1 pound, whereas there are more than 100,000 winged elm seed per pound. Not only seed, but also fruit size and weight vary substantially; a bushel of sweetgum fruits yields only 0.8 pound of seed, but a bushel of white oak fruit may yield 100 pounds of seed (table 15-23). Within-species and within-tree variations in seed size, shape, and weight are substantial, so the tabulated values should serve only as a general guide.

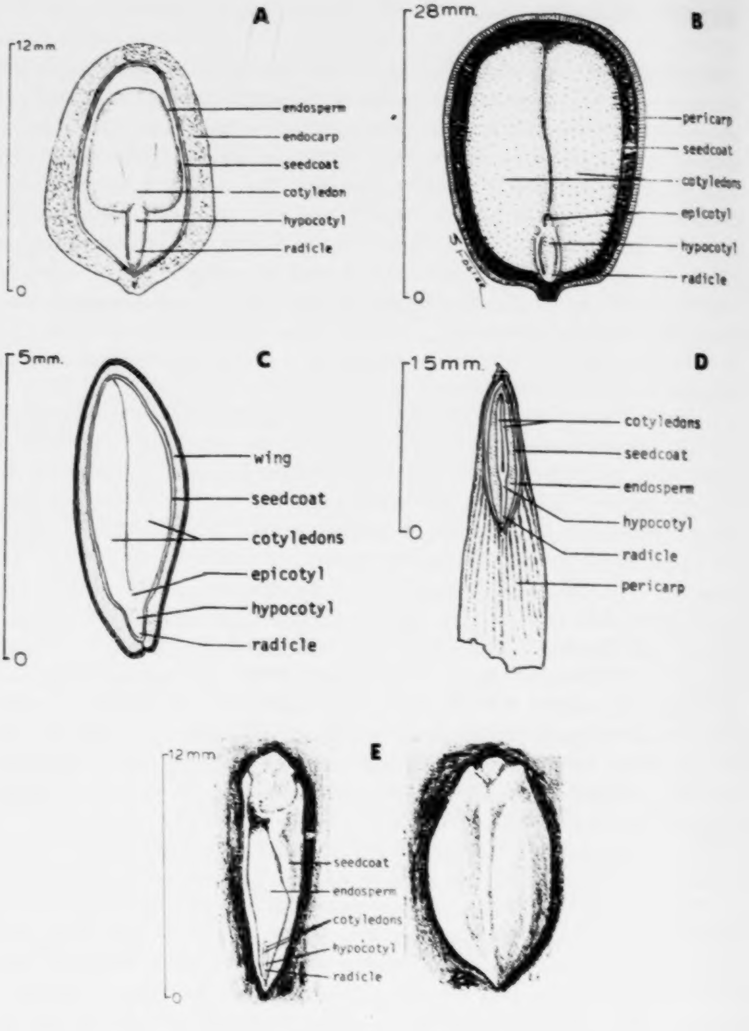
A
12mm
endosperm
endocarp
seedcoat
cotyledon
hypocotyl
radicle
0
B
28mm.
pericarp
seedcoat
cotyledons
epicotyl
hypocotyl
radicle
0
C
5mm.
wing
seedcoat
cotyledons
epicotyl
hypocotyl
radicle
0
D
15mm.
cotyledons
seedcoat
endosperm
hypocotyl
radicle
pericarp
0
E
12mm
seedcoat
endosperm
cotyledons
hypocotyl
radicle
0

Figure 15-20.—Seeds from five types of fruit borne by hardwoods growing on southern pine sites. (A) Drupe: longitudinal section through a stone of black tupelo. (B) Nut: longitudinal section through a northern red oak acorn. (C) Capsule: longitudinal section through a sweetgum seed separated from its capsule. (D) Samara: longitudinal section through the embryo of a green ash samara. (E) Aggregate: seeds of *Magnolia grandiflora* L. after removal of the fleshy layer; right, surface of the stony layer of the seedcoat; left, longitudinal section through the embryo. (Drawings after Schopmeyer 1974.)

TABLE 15-23.—*Seed bearing characteristics of pine-site hardwoods, fruit size, and seed weight* (Data from Schopmeyer 1974)

Species	Minimum seed-bearing age	Interval between large seed crops	Weight of seeds per bushel of fruit	Weight of seeds per 100 pounds of fruit	Cleaned seeds per pound[1]
	-------*Years*------		-----*Pounds*------		*No.*
Ash, green			7.2		20,950
Ash, white			12.5		8,470
Elm, American	15		2.2	50	70,900
Elm, winged					111,500
Hackberry (sugarberry)	15			50-75	2,500[2]
Hickory, bitternut	30	3-5	40	60-85	156
Hickory, mockernut	25	2-3	44	50-80	36
Hickory, pignut	30	1-2	40	65-85	200
Hickory, shagbark	40	1-3	30-38	35-38	100
Maple, red	4	1			22,860
Oak, black	20	2-3	41-49	20	245
Oak, blackjack					210-413[3]
Oak, cherrybark	25	1-2			580
Oak, chestnut	20	2-3		40-50	100
Oak, laurel	15	1			560
Oak, northern red	25	3-5	22-104	42-80	125
Oak, post	25	2-3	54		380
Oak, scarlet	20	3-5	30-60	40-50	235
Oak, Shumard	25	2-3	50		100
Oak, southern red	25	1-2	33-50	75-86	540
Oak, water	20	1-2	44-56		395
Oak, white	20	4-10	45-100	60-90	120
Sweetbay	10	1			7,530
Sweetgum	25	2-3	0.8		82,000
Tupelo, black				25	3,380
Yellow-poplar			6-8		10,000[2]

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[1] Air-dry basis.

[2] Data based on the Starkville, Mississippi, collection of F. T. Bonner.

[3] Halls (1977); Collins (1961); Goodrum et al. (1971).

Downs (1944) weighed fresh, well-developed acorns about 5 days after they dropped from oaks in Georgia and North Carolina, with results as follows:

Oak species	Acorns/pound
	Number
Black	241
Scarlet	194
White	166
Northern red	90
Chestnut	69

Reid and Goodrum (1957), after sampling oaks in west-central Louisiana and eastern Texas, concluded that acorn size varies within species too. For example, post oak acorns ranged from 188 to 493 per pound with an average of 269. They found that sound acorns of five oak species averaged 138 to 391 per pound when fresh and 217 to 521 when air-dried to 15 percent moisture content, as follows:

Oak species	Fresh	Air dry
	Acorns/pound	
White	138	217
Post	269	358
Blackjack	287	382
Southern red	288	383
Water	391	521

Significant variations in fruit size and weight occur diurnally and seasonally. Observations of fruits of red maple and northern red oak indicate that they shrink during the day and expand at night; the fluctuations in dimensions are related to vapor pressure deficit; i.e., expansion of fruits generally occurred when the vapor pressure deficit was decreasing or low, and contraction resulted when it was increasing or high (Chaney and Kozlowski 1969b).

The weight and diameter of acorns from cherrybark, Shumard, water, and white oaks growing in central Mississippi were observed by Bonner (1974b, 1976b) to increase more or less continuously from June through October; their moisture content, however, increased to a maximum of about 50 to 65 percent of fresh weight in early September and then declined to 40 or 50 percent by the end of October. In contrast to the seasonal changes in acorns, the fresh weight (about 8 grams) and moisture content (about 70 percent of fresh weight) of yellow-poplar fruits remain fairly constant from early July through October in Mississippi (Bonner 1976a).

SEED YIELD PER TREE AND PER ACRE

Seed yield data, either on a tree or acre basis, are scarce. Most available information is on the oaks, with some data on sweetgum and yellow-poplar. Most studies reveal considerable variation in production between trees and between sites. Annual variation in seed crops is also substantial. Readers interested in fruit yields of southern understory and browse species will find data of Lay (1962) and Halls (1973) useful.

Sweetgum. Kearney and Bonner (1968) found that in Mississippi sweetgum trees on Delta sites produced more seed than trees on loess and Coastal Plains sites; in the years 1965 and 1966, 42 percent of twigs on sweetgum trees growing on the three sites bore fruit, and each fruit averaged 30 full seed.

Yellow-poplar.—Carvell and Korstian (1955) found that on the Duke Forest in North Carolina numbers of fruit clusters and viable seeds per yellow-poplar trees were positively and linearly correlated with tree dbh (fig. 15-21). The average number of seeds per fruit cluster was 81. Yellow-poplar seed dissemination began in mid-October and reached its peak in early November; by the end of November seed fall was drastically reduced, but some seeds continued to fall throughout the winter. Yellow-poplar seed fall of 300,000 or more seeds per acre was not uncommon where several seed trees per acre were present.

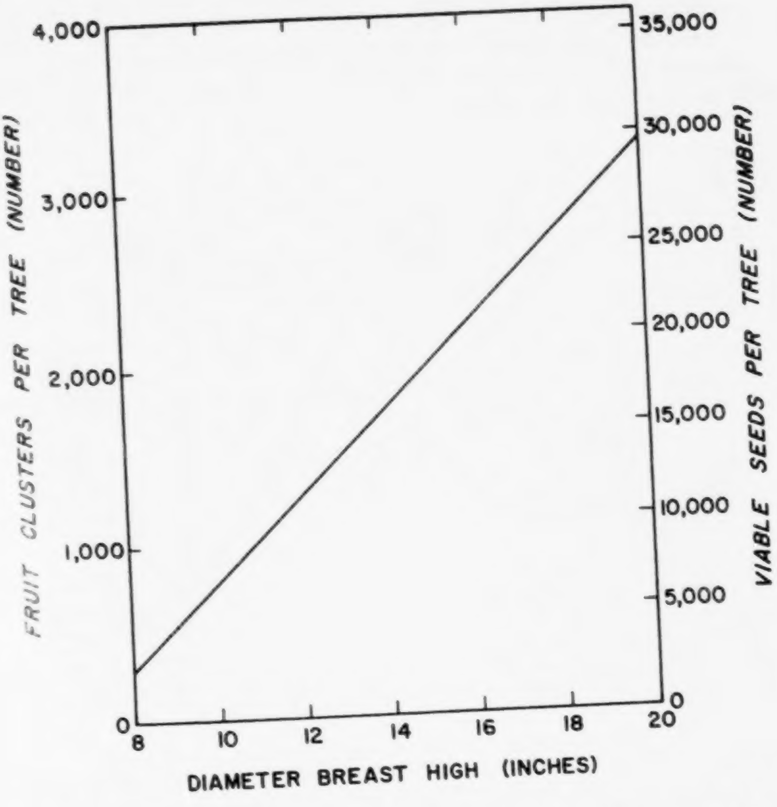

Figure 15-21.—The relationship between dbh of yellow-poplar and the number of fruit clusters per tree (left axis) and the number of viable seeds per tree (right axis). (Drawing after Carvell and Korstian 1955.)

Oaks, production per tree.—Sharp (1958), in discussing evaluation of oak mast yields, observed that red oak acorns mature the second year but female flowers (young acorns) are produced in axils of leaves on new growth; by the time they mature, they are hidden by the current year's leaves so as to appear to rest against their branch (fig. 15-22 left). Thus leaves obscure them from view when viewed from outside the crown, but they can be observed if viewed upward through the crown using the bright sky as background. White oak acorns mature the first year and thus appear at leaf level or slightly above (fig. 15-22 right), extending into the open; they are best observed with binoculars from outside the crown at distances up to 100 feet. Some twigs do not bear acorns, and the number borne on fruitful twigs varies substantially. Petrides et al. (1953), found that post oak yields in east Texas varied from less than 1 to as many as 130 acorns per 100 twigs depending on year, site, tree size, and time of observation during June, July, and August.

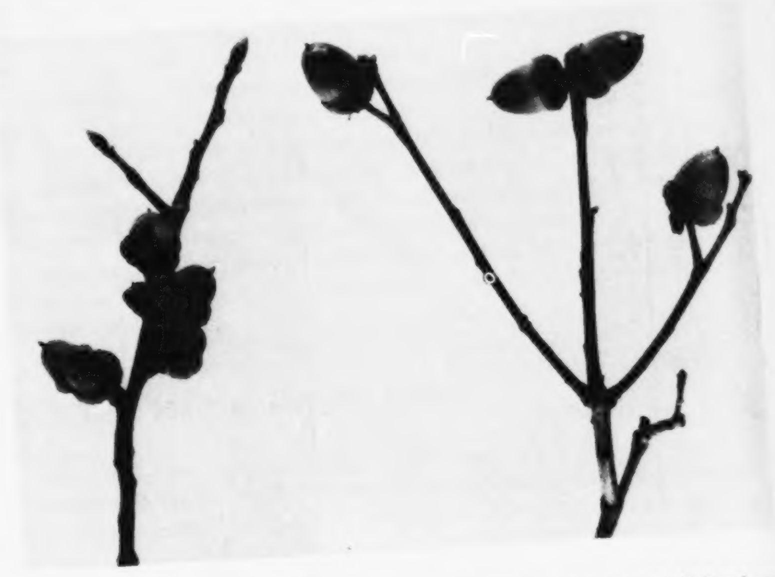

Figure 15-22.—Oak twigs with leaves removed to show acorn location. (Left) Southern red oak acorns set on second-year wood, good yield. (Right) White oak acorns on current year wood.

The oak species differ substantially in numbers of acorns produced per tree and in the relationship of this production to diameter; thus, 20-inch scarlet oak sampled in North Carolina and Georgia averaged about 3,000 acorns per tree per year, while chestnut oak of the same diameter averaged only about 600 (Downs and McQuilken 1944). While acorn yields from scarlet, black, and chestnut oaks increased continuously with increasing tree diameter, northern red and white oaks reached peak yields at 20 or 26 inches diameter and then decreased (fig. 15-23 and table 15-24).

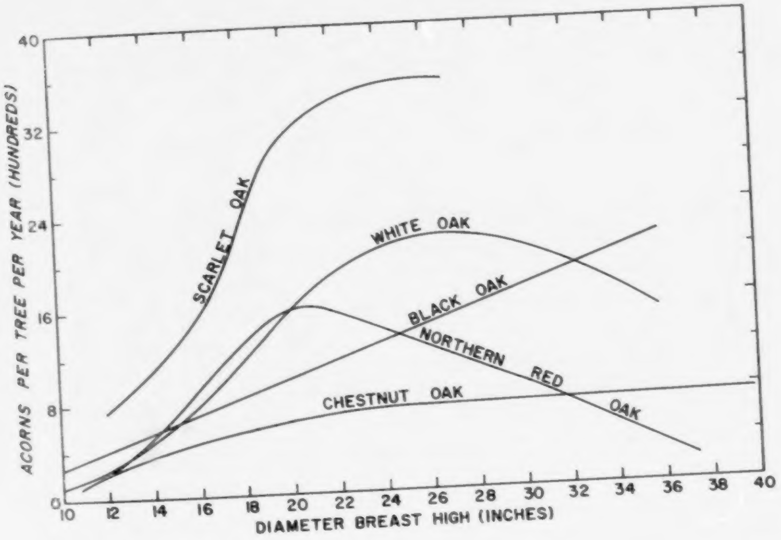

Figure 15-23.—Acorn production per tree per year for five oak species related to dbh; data are based on 7-year averages for 42 trees of each species. (Drawing after Downs and McQuilken 1944.)

Christisen (1955), studying five oak species in the Missouri Ozarks, found that acorn yields vary significantly from year to year, but that general and simultaneous acorn crop failures of all species are unlikely. He observed no consistent relationship between acorn production and measurable tree characteristics, although there was a tendency for large-crowned oaks to produce more acorns than those with small crowns. Over a 6-year-period, oaks 8 to 25 inches in dbh in two Missouri counties produced average numbers of mature acorns per tree annually as follows:

Oak species	Dent County	Butler County
	------Number per tree------	
Black	900	1,500
Blackjack	700	—
Scarlet	500	2,400
Post	200	—
White	1,100	700

TABLE 15-24.—*Weight*[1] *of annual acorn crop per tree related to dbh of trees of five oak species in Bent Creek Experimental Forest, North Carolina* (Data from Downs 1944)

Tree dbh (inches)	Oak species				
	Black	Chestnut	Northern red	Scarlet	White
	Pounds/tree/year, average				
10	1	0.9	0.4	2.5	0.7
12	1.7	3.0	2.2	3.9	1.4
14	2.3	5.0	5.7	5.6	2.8
16	2.8	6.0	10.0	8.0	4.5
18	3.4	8.1	14.5	12.1	6.7
22	4.6	9.8	17.1	17.5	11.3
26	5.8	10.5	13.8	18.3	13.1
30	7.0	10.8	10.0	18.3	12.5

[1] For fresh, well-developed acorns about 5 days after dropping from trees.

Collins (1961), working in Louisiana, observed good mast yields on blackjack, post, southern red, water, and white oaks measuring 10 inches dbh or larger. Reid and Goodrum (1957), also using data from Louisiana, tabulated the relationship between tree dbh and seed yield for five upland oak species (table 15-25); most production came from the larger diameter trees with well-developed crowns. Trees in open stands yielded more acorns per tree than those in dense stands. They also observed that oaks of mast-bearing age do not all produce mast every year, even in bumper crop years; the annual average percentage of mast-bearing trees (10-inch dbh and larger) varied by species, as follows:

Oak species	Trees producing acorns (6-year average)
	Percent
Water	93
Blackjack	92
Southern red	67
White	60
Post	54

From studies of chestnut and white oaks in Pennsylvania, Sharp and Sprague (1967) concluded that good acorn crops were obtained in years when a warm 10-day period occurred late in April, with average night temperatures of 55 to 60°F, followed by cooler periods (45 to 50°F) for 13 to 20 days early in May. During years when April remained cool and was followed by warm days and nights in May, acorn production was poor.

TABLE 15-25.—*Average annual yield of acorns per tree, related to breast-height diameter of trees of five oak species observed in Louisiana* (Data from Reid and Goodrum 1957)[1]

Tree dbh (inches)	Post Oak		White oak		Blackjack oak		Southern red oak		Water oak	
	Number	Weight[2]	Number	Weight[2]	Number	Weight[2]	Number	Weight[2]	Number	Weight[2]
		Pounds		*Pounds*		*Pounds*		*Pounds*		*Pounds*
4	40	0.2(0.1)	—	—	—	—	—	—	—	—
6	210	.8(.6)	—	—	—	—	—	—	—	—
8	380	1.4(1.1)	40	0.3(0.2)	120	0.4(0.3)	—	—	225	0.6 (0.4)
10	550	2.0(1.5)	270	2.0(1.2)	490	1.7(1.3)	140	0.5 (0.4)	1,075	2.8 (2.1)
12	720	2.7(2.0)	500	3.6(2.3)	865	3.0(2.3)	300	1.0 (.8)	1,950	5.0 (3.7)
14	890	3.3(2.5)	730	5.3(3.4)	1,245	4.3(3.3)	600	2.1 (1.6)	2,800	7.2 (5.4)
16	1,060	3.9(3.0)	960	6.9(4.4)	1,620	5.6(4.2)	1,080	3.8 (2.8)	3,700	9.5 (7.1)
18	1,230	4.6(3.4)	1,195	8.6(5.5)	2,000	7.0(5.2)	1,860	6.5 (4.9)	4,550	11.6 (8.7)
20	1,395	5.2(3.9)	1,425	10.3(6.6)	2,280	7.9(6.0)	3,040	10.6 (7.9)	5,450	13.9(10.5)
22	1,560	5.8(4.4)	1,660	12.0(7.7)	2,760	9.6(7.2)	4,700	16.3(12.3)	6,350	16.2(12.2)
24	—	—	1,890	13.7(8.7)	3,125	10.9(8.2)	6,940	24.1(18.1)	7,250	18.5(13.9)
26	—	—	2,105	15.2(9.7)	—	—	9,140	31.7(23.9)	—	—

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[1] Average for the years 1950 through 1956.

[2] The first value tabulated is the fresh weight, 1 to 5 days off tree; the second value (in parentheses) is the air-dry weight, i.e., about 15-percent moisture content based on ovendry weight.

Heeren (1969) found from a 1-year observation of cherrybark oak growing on a mineral pocosin in coastal North Carolina, that nearly 90 percent of all sound undamaged acorns fell during the month of November. Cypert and Webster (1948) noted that water oak in Arkansas began dropping their acorns in early September and continued into December; in 1938 acorn fall peaked in late September, in 1939 in the third week in November.

The 15 water oak trees observed by Cypert and Webster (1948) measured from 12 to 31 inches in dbh and had annual acorn yields per tree from 96 to 28,360. There were large differences in acorn yields among trees of comparable size and age on similar sites. Annual variations were also substantial; for example, one 18-inch tree produced 274 acorns in 1938, 2,132 in 1939, and 7,670 in 1940. Acorn production by northern red and white oaks in West Virginia also was unrelated to site and varied greatly with year and among trees of the same size on similar sites (Tryon and Carvell 1962).

Oaks, production per acre.—Acorn crops can vary from very low levels to 250,000 or more acorns per acre; in some years the white oaks will produce heavily while the red oaks will have practically no yield, and vice versa (Olson and Boyce 1971). Downs (1944) found that oak stands on the Bent Creek Experimental Forest near Asheville, N.C. averaging about 27 oak trees 10 inches and larger in dbh per acre produced about 150 pounds (fresh-weight basis) per acre per year.

Beck and Olsen (1968) observed substantial variations among years and species in numbers of well-developed acorns produced annually per acre (fig. 15-24). In the Ozark National Forest of Arkansas, Segelquist et al. (1969) observed acorn yields (ovendry weight basis) of 10 to 406 pounds per acre over a 5-year period, with average of 141 pounds per acre at the Caney Wildlife enclosure and 80 pounds per acre at the Big Spring enclosure—each about 600 acres in size.

In West Virginia, Tryon and Carvell (1962) found that over a 5-year period northern red oaks produced an average total crop of 170 acorns per milacre of crown area, and white oaks an average of 96; of the total crop of acorns, 35 percent were immature. Of the total mature acorn crop only 13.5 were sound, insects and animals having damaged the rest.

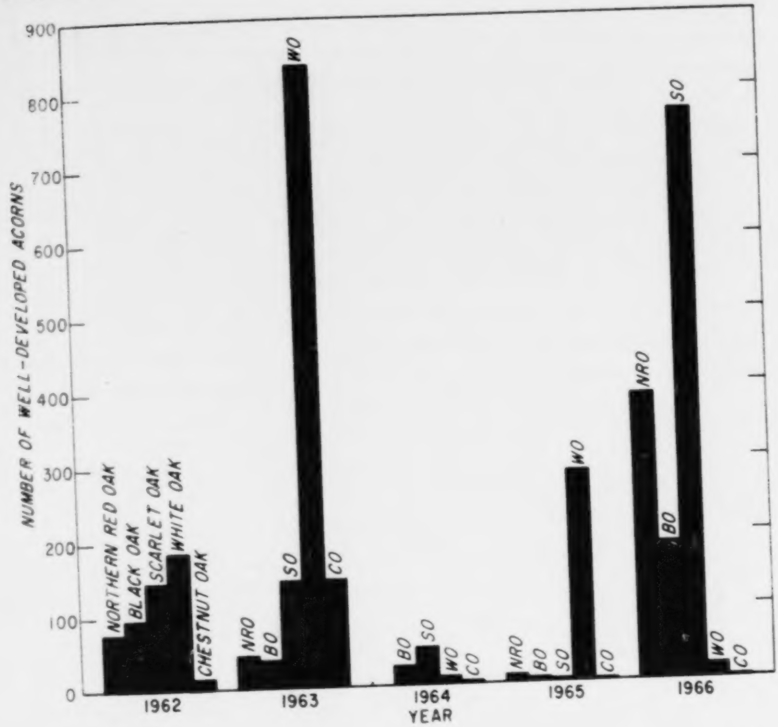

Figure 15-24.—Total yearly production of well-developed acorns per acre by species in mixed oak stands near Asheville, N.C. (Drawing after Beck and Olson 1968.)

Beck's (1977) summation of 12 years of data on acorn yield at the Bent Creek Forest indicated that each acre of mixed oak stand produced an average of 289 pounds (fresh weight) of well-developed acorns annually. Acorn yields were over 500 pounds per acre for 4 of the 12 years, over 75 pounds per acre for 9 years, and below 30 pounds per acre for 3 years. The really poor years did not occur consecutively, but were bracketed by fairly productive years. Acorn yields of the five species per year per square foot of basal area averaged over the 12 years were somewhat different than those predicted by Downs' data (table 15-24), as follows:

Oak species	Observed by Beck (1977)	Predicted by Downs (1944)
	Pounds/square foot of basal area	
Northern red	12.2	4.7
White	8.3	4.3
Scarlet	3.0	4.4
Chestnut	2.4	2.4
Black	1.6	1.8

Considering the extreme variation in observed acorn yields, generalizations are difficult. Tabulations in the Wildlife Habitat Management Handbook (U.S. Department of Agriculture, Forest Service 1969) represent such an effort (table 15-26).

After harvest.—Fruit yields after a clearcut harvest consist largely of herbaceous and understory browse species, many of which are food for wildlife, including songbirds. Yields vary considerably in relation to site preparation treatments. In east Texas, 3 years after a clearcut, fruit yields from browse ranged from 37 pounds/acre on plots with intensive mechanical treatments to 107 pounds/acre on burned plots (Stransky and Richardson 1977).

TABLE 15-26.—*Annual acorn yield (fresh-weight basis) of two groups of oaks of two diameter classes related to basal area per acre* (U.S. Department of Agriculture, Forest Service 1969)[1]

Basal area per acre (square feet)	Red oak group		White oak group	
	Dbh 9 to 14 inches	Dbh 15+ inches	Dbh 9 to 14 inches	Dbh 15+ inches
	Pounds/acre			
2	5 (2)	7 (5)	4 (6)	5 (6)
4	9 (4)	14 (9)	7(11)	11(12)
6	14 (6)	21(14)	11(17)	16(17)
8	18 (8)	28(19)	14(23)	22(23)
10	23(11)	35(24)	18(29)	27(29)
12	28(13)	42(28)	21(34)	33(35)
14	32(15)	49(33)	25(40)	38(41)
16	37(17)	56(38)	28(46)	44(47)
18	41(19)	63(42)	32(51)	49(52)
20	46(21)	70(47)	35(56)	55(58)
22	50	77	39	61
24	55	84	42	66
26	60	91	46	72
28	64	98	49	78
30	69	105	53	83
32	73	112	56	89
34	78	119	60	94
36	82	126	64	100
38	87	133	67	106
40	92	140	71	111
50	115	175	89	138
60	138	210	106	166

[1] The first value tabulated is for mountain forests in the South in which the red oak group includes northern red, black, and scarlet oaks, and the white oak group includes chestnut and white oaks. The second value (in parentheses) is for southern plains forests where the red oak group includes southern red and blackjack oaks, and the white oak group includes post oak and white oaks.

ACORN QUALITY

During 7 years' collection at North Carolina's Bent Creek Experimental Forest, 53 percent of all acorns were imperfectly developed (Downs 1944).

In Beck's (1977) 12-year study on this forest an average of 35 percent of all the well-developed acorns were infested by insects, primarily weevils, and were at least partially unavailable for wildlife. Insects infested only 29 percent of the well-developed acorns in better seed years and 67 percent in the poorest years. Chestnut and northern red oaks had the least insect damage, followed by white, black, and scarlet oaks in that order.

In Louisiana, Reid and Goodrum (1957) found from 74 to 90 percent of well-developed acorns were sound, as follows:

Oak species	Percent sound
Blackjack	74
Post	76
Southern red	77
White	90

In the Missouri Ozarks, more than half of all mature acorns may be damaged by insects, as follows (Burns et al. 1954):

Oak species	Missouri county		
	Butler	Dent	Taney
	Percent damaged by insects		
Black	46	72	61
Blackjack	—	71	60
Scarlet	48	70	—
Post	—	87	80
White	59	72	57

Some details on identity and action of seed-destroying insects are provided in Section 11-7.

UTILIZATION BY WILDLIFE

Several scientists have reported on the use of pine-site hardwood seeds as food by a wide range of birds and animals. For squirrels, hickory nuts provide a most efficient food in fall and spring, while acorns are the most efficiently digested food in winter (Smith and Follmer 1972). Short (1976) observed that acorns of black, northern red, water, and southern red oaks provide squirrels with more energy than those of white and post oaks; acorns of the latter, however, seem to be preferred by Louisiana squirrels. Wildlife of the Missouri Ozarks were reported by Burns et al. (1954) and Christisen (1955) to have no evident preferences for any species of acorn. Reid and Goodrum (1957) estimated from studies in Louisiana and Texas that acorns provide three-quarters of the diet of squirrels and turkeys and one-half that of deer and quail during the principal period of acorn fall—about 120 days.

To satisfy a representative game population for 120 days would require about 25.3 pounds (air-dry basis) of sound acorns per acre, as follows (Reid and Goodrum 1957):

Wildlife	Density	Acorn requirement
		Pounds/acre
Deer	1 in 20 acres	9.0
Gray squirrel	1 in 2 acres	7.2
Fox squirrel	1 in 3 acres	5.7
Mice or rats	2 per acre	2.0
Turkey	1 to 50 acres	1.2
Quail	1 to 10 acres	.1
Others	1 to 10 acres	.1
Total		25.3

Reid and Goodrum noted that to get 25 pounds of sound fallen acorns for ground feeders, at least 48 pounds per acre must be produced because of insect damage and consumption by arboreal wildlife.

Shaw (1971), after reviewing the literature on acorn requirements by wildlife, concluded that 100 pounds of acorns per acre (total tree crown production) is a reasonable goal when managing forests for acorn-consuming game and non-game species.

Before leaving the subject of seed utilization for animal food, it must be noted that hickory nuts have been consumed by mankind for centuries. The interested reader will find a recipe for no-knead, water-rising twists utilizing shagbark hickory nut kernels in Downs (1949).

CHEMICAL ANALYSIS

Fruits and seeds that are present during autumn and winter in pine-site forests are vitally important foods for wildlife because mature forbs, grasses, and woody twigs are of limited nutritional value at these seasons. While acorns are palatable and digestible by much of wildlife during seasons when other quality foods are uncommon, they have low **protein content** (about 6 percent of dry weight) and should not be expected to alleviate protein deficiencies from eating other low-protein forages during autumn and winter. Some other seeds, such as those of sweetgum, have higher protein content—more than 25 percent (Short and Epps 1976).

Crude fat content is an index of potential energy of a food; this analytical fraction is comprised of all the ether solubles including the true fats. Crude fat content is high in kernels of mockernut hickory (about 64 percent) and measures more than 25 percent in kernels of bitternut hickory. White oak acorns and seeds of yellow-poplar, however, have crude fat contents no greater than 2 percent of dry weight. Acorns of the white oak group average only 4.3 percent crude fat while those of the red oak group averaged 17.9 percent (Short and Epps 1976).

Most seeds and fruits of high protein content also have high **phosphorus content.** Phosphorus requirements for many forest consumers are unknown, but Halls (1970c) cited required levels of 0.75-0.80 percent in the diet of growing and developing turkeys, 1.0 percent for quail, 0.5 percent for squirrels, and above 0.25 percent for mature whitetail deer. Seeds of southern pine, mockernut hickory, sweetgum, black tupelo, and sugarberry all have more than 0.30 percent phosphorus (Short and Epps 1977). Seeds of green ash, winged elm, hackberry, and shagbark hickory also have high phosphorus content (table 15-27). Acorns are particularly low in phosphorus content, having only about 0.1 percent.

Crude fiber content is negatively correlated with estimates of seed digestibility. Hickory nut kernels have low fiber content (about 3 percent), while acorns average about 18 percent. **Silica content,** which reduces digestibility of forage dry matter, is low in acorns (about 0.01 percent) but was found to be 3 percent in the fleshy fruits of sugarberry. **Calcium content** such that calcium:phosphorus ratios are in the range 1:2 to 2:1 are considered favorable for animal metabolism. Some acorns have ratios outside this range; sugarberry fruit was observed to have 11.3 percent calcium content. **Digestibility** of fruits and seeds, as measured on ruminally cannulated goats, is about 68 percent for acorns, but more than 80 percent for hickory nut kernels (Short and Epps 1976). Of crude protein in acorns, Matschke et al. (1973) found that hogs digested 30 to 65 percent.

Data on **average chemical contents** of seeds of pine-site hardwoods are summarized in table 15-27. Data on **seasonal variability** in crude fat, carbohydrate, and mineral contents of yellow-poplar and sweetgum seeds and acorns from cherrybark, Shumard, water, and white oaks can be found in Bonner (1970, 1974ab, 1976ab). In general, crude fat percentage increases sharply in late summer (but not in yellow-poplar seeds); nitrogen, calcium, magnesium, and phosphorus percentages decline slightly from July through October. Bonner (1970) provided some suggestions for determining visually when seed are mature, as follows:

Species	Seeds are mature
Sweetgum	When the lustrous green color of the fruit head fades and the spines turn brown (September through October in central Mississippi)
Oaks	When the exposed end of the acorn turns brown—usually in October
Green and white ash	When green color of samaras fades to brown—usually in October in central Mississippi
Yellow-poplar	When the exterior carpels turn tan to light brown—usually in October in the South

TABLE 15-27.—*Chemical composition of fruits and seeds of pine-site hardwoods as summarized by Halls (1977), with additions from Bonner (1971)*

Species	Part analyzed	Crude protein	Crude fat	Crude fiber	Nitrogen-free extract or total carbohydrates	P	Ca	Mg	Reference
		Percent of dry weight							
Ash, green	Seed	14.5	9.2	—	20.8[a]	0.34	0.67	0.08	Bonner (1971)
Ash, white	Seed	8.5	8.7	—	23.9[a]	.22	.25	.13	Bonner (1971)
Elm, American	Seed	14.8	7.9	—	11.0[a]	.38	.53	.20	Bonner (1971)
Elm, winged	Seed	27.4	15.3	—	8.9[a]	.52	.51	.20	Bonner (1971)
Hackberry	Fruit	9.5	6.9	8.9	60.0	.30	11.30	—	Schopmeyer (1974); Short and Epps (1976)
Hickory, bitternut	Kernel	7.5	48.3	2.4	41.3	.24	.16	—	Schopmeyer (1974); Short and Epps (1976)
Hickory, bitternut	Seed, husked	3.3	30.8	—	17.1[a]	.12	.46	—	Bonner (1974ab)
Hickory, mockernut	Kernel	11.9	82.6	2.9	2.0	.35	.14	—	Schopmeyer (1974); Short and Epps (1976)
Hickory, mockernut	Seed, husked	3.7	20.0	—	12.7[a]	.08	.22	—	Bonner (1974ab)
Hickory, shagbark	Kernel	13.3	74.4	1.5	8.8	.37	—	—	Schopmeyer (1974); Bonner (1974ab)
Hickory, shagbark	Seed, husked	5.9	37.4	—	13.0[a]	.15	.20	.08	Bonner (1971)
Maple, red	—	—	—	—	—	—	—	—	—
Oak, black	Acorn	5.7	17.5	16.6	57.9	.10	.19	—	Short (1976)
Oak, blackjack	Acorn	7.0	16.2	19.0	57.4	.11	.26	—	Short and Epps (1976)
Oak, blackjack	Acorn	6.3	10.7	20.9	60.1	.09	.37	—	Hastings (1966)
Oak, cherrybark	Acorn	4.0	15.8	—	29.5[a]	.06	.27	.06	Bonner (1971)
Oak, chestnut	Acorn	4.6	1.0	29.4	64.6	.11	.16	—	Schopmeyer (1974); Short and Epps (1976)
Oak, chestnut	Acorn	6.9	5.1	2.6	83.2	.15	[b]	—	Waino and Forbes (1941)
Oak, chestnut	Acorn	6.4	3.3	15.2	72.9	.12	.14	—	King and McClure (1944)
Oak, laurel	Acorn	5.0	26.8	3.4	62.3	.10	.09	—	Schopmeyer (1974); Beckwith[c]
Oak, northern red	Acorn	4.9	14.0	26.4	52.3	.08	.15	—	Short (1976)
Oak, post	Acorn	5.2	5.7	19.5	66.7	.11	.40	—	Schopmeyer (1974); King and McClure (1944)
Oak, post	Acorn	3.8	5.2	—	37.9[a]	.08	.25	.06	Bonner (1971)
Oak, post	Acorn	8.3	5.1	15.8	—	.10	.15	—	Short and Epps (1976)

TABLE 15-27.—*Chemical composition of fruits and seeds of pine-site hardwoods as summarized by Halls (1977), with additions from Bonner (1971)*—Continued

Species	Part analyzed	Crude protein	Crude fat	Crude fiber	Nitrogen-free extract or total carbo-hydrates	P	Ca	Mg	Reference
		Percent of dry weight							
Oak, post	Acorn	6.8	6.7	18.1	65.3	.09	.22	—	Short (1976)
Oak, scarlet	Acorn	4.2	14.6	—	35.6[a]	.07	.18	.07	Bonner (1971)
Oak, Shumard	Acorn	3.8	9.8	—	29.3[a]	.06	.27	.06	Bonner (1971)
Oak, southern red	Acorn	6.5	15.8	18.1	59.2	.10	.21	—	Schopmeyer (1974); Short and Epps (1976)
Oak, southern red	Acorn	4.2	15.6	20.6	57.7	.08	.43	—	King and McClure (1944)
Oak, southern red	Acorn	5.1	17.0	—	23.0[a]	.08	.32	—	Bonner (1974ab)
Oak, southern red	Acorn	7.0	22.7	19.9	48.6	.11	.23	—	Short (1976)
Oak, water	Acorn	3.8	20.3	—	25.8	.06	.32	.07	Bonner (1971)
Oak, water	Acorn	5.3	20.5	16.7	57.1	.08	.28	—	Short and Epps (1976)
Oak, water	Acorn	4.9	21.1	17.6	54.0	.08	.18	—	Short (1976)
Oak, white	Acorn	6.3	6.3	2.5	82.3	.16	[b]	—	Schopmeyer (1974); Wainio and Forbes (1941)
Oak, white	Acorn	4.6	2.9	—	46.6[a]	.08	.22	—	Bonner (1971)
Oak, white	Acorn	4.1	1.2	19.9	74.4	.08	.27	—	Short and Epps (1976)
Oak, white	Acorn	4.6	5.8	18.6	68.3	.09	.18	—	Short (1976)
Sugarberry	Seed	7.2	4.5	—	34.8[a]	.21	.88	.69	Bonner (1971)
Sweetgum	Seed	26.7	23.7	20.2	27.9	.55	.85	—	Short and Epps (1976)
Sweetgum	Seed	25.3	26.2	—	11.6[a]	.69	1.51	.28	Bonner (1971)
Tupelo, black	Seed	3.5	10.4	—	14.5[a]	.18	.06	.09	Bonner (1971)
Tupelo, black	Fruit	6.4	14.4	35.8	42.7	.35	.31	—	Short and Epps (1976)
Yellow-poplar	Seed	2.9	1.9	—	19.3[a]	.08	.38	.18	Bonner (1971)

[a] Total carbohydrates.
[b] Trace.
[c] Unpublished.

15-8 LITERATURE CITED

Akhtar, M. A., G. L. Rolfe, and L. E. Arnold. 1976. Litter decomposition in oak-hickory forests in southern Illinois. For. Res. Rep. No. 76-6, 3 p. Agric. Exp. Stn., Univ. of Ill., Urbana-Champaign, Ill.

Auchmoody, L. R. 1974. Nutrient composition of blades, petioles, and whole leaves from fertilized and unfertilized yellow-poplar. U.S. Dep. Agric. For. Serv., Res. Note NE-198. 5 p.

Auchmoody, L. R. and K. P. Hammack. 1975. Foliar nutrient variation in four species of upland oaks. U.S. Dep. Agric. For. Serv., Res. Pap. NE-331. 16 p.

Barton, G. M. 1976. Foliage. Part II. Foliage chemicals, their properties and uses. Appl. Polym. Symp. No. 28, pp. 465-484. New York, N.Y.: John Wiley & Sons, Inc.

Barton, G. M., J. A. McIntosh, and S. Chow, 1978. The present status of foliage utilization. *In* AIChE Symp. Ser. 74(177):124-131. (Amer. Inst. Chem. Eng.)

Bateman, B. A. 1959a. Timber and game: a desirable combination. LSU For. Note. No. 32, 2p. Louisiana State Univ., Baton Rouge, La.

Bateman, B. A. 1959b. Value of hardwoods in forest game habitat in Louisiana. LSU For. Note No. 31, 2 p. Louisiana State Univ., Baton Rouge, La.

Beck, D. E. 1977. Twelve-year acorn yield in southern Appalachian oaks. U.S. Dep. Agric. For. Serv., Res. Note SE-244. 8 p.

Beck, D. E., and D. F. Olson, Jr. 1968. Seed production in southern Appalachian oak stands. U.S. Dep. Agric. For. Serv., Res. Note SE-91. Southeast. For. Exp. Stn., Asheville, N. C. 7 p.

Biswell, H. H. and M. D. Hoover. 1945. Appalachian hardwood trees browsed by cattle. J. of For. 43:675-676.

Blackmarr, W. H. 1971. Equilibrium moisture content of common fine fuels found in southeastern forests. U.S. Dep. Agric. For. Serv., Res. Pap. SE-74. 8 p.

Blair, R. M. 1971. Forage production after hardwood control in a southern pine-hardwood stand. For. Sci. 17(3):279-284.

Blair, R. M., and L. E. Brunett. 1980. Seasonal browse selection by deer in a southern pine-hardwood habitat. J. Wildl. Manag. 44(1):79-88.

Blow, F. E. 1955. Quantity and hydrologic characteristics of litter under upland oak forests in eastern Tennessee. J. of For 53:190-195.

Bonner, F. T. 1970. Hardwood seed collection and handling. *In* Silviculture and management of southern hardwoods, pp 53-63. Proc. of La. State Univ. 19th annual for. symp.

Bonner, F. T. 1971. Chemical contents of southern hardwood fruits and seeds. U.S. Dep. Agric. For. Serv., Res. Note SO-136. 3 p.

Bonner, F. T. 1974a. Chemical components of some southern fruits and seeds. U.S. Dep. Agric. For. Serv., Res. Note SO-183. 3 p. South. For. Exp. Stn., New Orleans.

Bonner, F. T. 1974b. Maturation of acorns of cherrybark, water, and willow oaks. For. Sci. 20:238-242.

Bonner, F. T. 1976a. Maturation and collection of yellow-poplar seeds in the Midsouth. U.S. Dep. Agric. For. Serv., Res. Pap. So-121. 8 p.

Bonner, F. T. 1976b. Maturation of shumard and white oak acorns. For. Sci. 22:149-154.

Burns, P. Y., D. M. Christisen, and J. M. Nichols. 1954. Acorn production in the Missouri Ozarks. Bull. No. 611, Univ. Mo. Agric. Exp. Stn., Columbia. 8 p.

Carpenter, S. B. and N. D. Smith. 1975. Stomatal distribution and size in southern Appalachian hardwoods. Can. J. of Bot. 53(11):1153-1156.

Carvell, K. L., and C. F. Korstian. 1955. Production and dissemination of yellow-poplar seed. J. For. 53:169-170.

Chandler, R. F., Jr. 1941. The amount and mineral nutrient content of freshly fallen leaf litter in the hardwood forests of central New York. J. Amer. Soc. Agron. 33:859-871.

Chaney, W. R. 1970. A device for continuous monitoriing of changes in leaf thickness. For. Sci. 16:56.

Chaney, W. R. and T. T. Kozlowski. 1969a. Seasonal and diurnal changes in water balance of fruits, cones, and leaves of forest trees. Can. J. of Bot. 47:1407-1417.

Chaney, W. R. and T. T. Kozlowski. 1969b. Seasonal and diurnal expansion and contraction of fruits of forest trees. Can. J. of Bot. 47:1033-1038.

Christisen, D. M. 1955. Yield of seed by oaks in the Missouri Ozarks. J. of For. 53(6):439-441.

Chow, S. 1977. Foliage as adhesive extender: a progress report. *in* Proc. of the 11th Washington State Univ. symp. on particleboard, pp. 89-98. Pullman, Wa.: Washington State Univ.

Clark, E. W., J. D. White, and J. A. Richmond. 1970. Chemical changes with maturation of hickory and oak foliage. J. Mitchell Soc. 86:169-170.

Coile, T. S. 1937. Composition of the leaf litter of forest trees. Soil Sci. 43:349-355.

Colannino, A. 1976. Weight equations for white oak and chestnut oak in northern West Virginia. MS Thesis. West Va. University, Morgantown. 75 p.

Collins, J. O. 1961. Ten year acorn mast production study in Louisiana. Louisiana Wildl. and Fish. Comm. Projs. 24-R and 29-R. 33 p.

Crawford, H. S. 1976. Relationships between forest cutting and understory vegetation: an overview of eastern hardwood stands. U.S. Dep. Agric. For. Serv., Res. Pap. NE-349. 9 p.

Crawford, H. W., J. B. Whelan, R. F. Harlow, and J. E. Skeen. 1975. Deer range potential in selective and clearcut oak-pine stands in southwestern Virginia. U.S. Dep. Agric. For. Serv., Res. Pap. SE-134. 11 p.

Crosby, J. S. and R. M. Loomis. 1974. Some forest floor fuelbed characteristics of black oak stands in southeast Missouri. U.S. Dep. Agric. For. Serv., Res. Note NC-162. 4 p.

Cushwa, C. T., R. L. Downing, R. F. Harlow, and D. F. Urbston. 1970. The importance of woody twig ends to deer in the Southeast. U.S. Dep. Agric. For. Serv., Res. Pap. SE-67. 11 p.

Cypert, E., and B. S. Webster. 1948. Yield and use by wildlife of acorns of water and willow oaks. J. Wildl. Manage. 12:227-231.

Davies, W. J. and T. T. Kozlowski. 1974. Stomatal responses of five woody angiosperms to light intensity and humidity. Can. J. Bot. 52:1525-1534.

Davies, W. J., T. T. Kozlowski, and J. Pereira. 1974. Effect of wind on transpiration and stomatal aperture of woody plants. *In* Mechanisms of regulation of plant growth. Bull. 12, pp. 433-438. Wellington, N.Z.: The Royal Soc. of N.Z.

Day, F. P., Jr., and C. D. Monk. 1974. Vegetation patterns on a southern Appalachian watershed. Ecology 55:1064-1074.

Dickerson, B. P. 1972. Changes in the forest floor under upland oak stands and managed loblolly pine plantations. J. of For. 70:560-562.

Dickson, R. E., and P. R. Larson. 1977. Muka from *Populus* leaves: A high feed supplement for livestock. TAPPI For. Biol./Wood Chem. Conf., Madison, Wis. June 20-22. p. 95-99.

Downs, A. A. 1944. Estimating acorn crops for wild life in the southern Appalachians. J. of Wildlife Manage. 8(4):339-340.

Downs, A. A. 1949. Trees and food from acorns. North. Nut Growers Assoc. Rep. 1949:177-180.

Downs, A. A. and W. E. McQuilken. 1944. Seed production of southern Appalachian oaks. J. of For. 42:913-920.

Dunlap, M. E. 1932. The drying rate of hardwood-forest leaves. J. of For. 30(4):421-423.

Finn, R. F. 1953. Mineral content of leaves clue to white oak site quality. U.S. Dep. Agric. For. Serv. Tech. Pap. No. 135. 12 p. Cent. States For. Exp. Stn.

Fowells, H. A., compiler. 1965. Silvics of forest trees of the United States. Agric. Handb. 271, U.S. Dep. Agric. For. Serv. 762 p.

Fuller, H. J., and O. Tippo. 1949. College botany. New York: Henry Holt and Company. 993 p.

Gabriel, W. J. 1958. Genetic differences in juvenile shumard oak. U.S. Dep. Agric. For. Serv., Res. Note No. 81. 3 p. Northeast. For. Exp. Stn., Upper Darby, Pa.

Gill, J. D., J.W. Thomas, W. M. Healy, J. C. Pack, and H. R. Sanderson. 1975. Comparison of seven forest types for game in West Virginia. The J. of Wildl. Manage. 39(4):762-768.

Gilmore, A. R., W. A. Geyer, and W. R. Boggess. 1968. Microsite and height growth of yellow-poplar. For. Sci. 14:420-426.

Gist, C. S. W. T. Swank. 1974. An optical planimeter for leaf area determination. The Amer. Midl. Nat. 92(1):213-217.

Goodrum, P. D., V. H. Reid, and C. E. Boyd. 1971. Acorn yields, characteristics, and management criteria of oaks for wildlife. J. Wildl. Manage. 35:520-532.

Gysel, L. W., J. H. Cooley, and F. Stearns. 1972. Timber and wildlife implications of pine conversion methods on poor oak sites. J. of For. 70:272-274.

Halls, L. K. 1970. Growing deer food amidst southern timber. J. of Range Manage. 23(3):213-215.

Halls, L. K. 1970. Improving wildlife habitat in pine-hardwood forests of the southern United States. *In* Trans. of the ninth Int. Congr. of Game Biol., pp. 151-153. Int. Union of Game Biol., Moscow.

Halls, L. K. 1970c. Nutrient requirements of livestock and game. *In* Range and Wildlife Habitat Evaluation—A research symposium. U.S. Dep. Agric. Misc. Publ. No. 1147.

Halls, L. K. 1973. Flowering and fruiting of southern browse species. U.S. Dep. Agric. For. Serv., Res. Pap. SO-90. 10 p.

Halls, L. K. 1977. Southern fruit-producing woody plants used by wildlife. U.S. Dep. Agric. For. Serv., Gen. Tech. Rep. SO-16. 235 p.

Halls, L. K. 1978. Effect of timber harvesting on wildlife, wildlife habitat and recreation values. *In* Complete tree utilization of southern pine: symp. proc., New Orleans, La., April 17-19. C. W. McMillin, ed. For. Prod. Res. Soc., Madison, Wis., p. 108-114.

Halls, L. K. [In Press.] Ecology and management of white-tail deer. Wildlife Management Institute.

Halls, L. K. and R. Alcaniz. 1970. Forage yields in an east Texas pine-hardwood forest. J. of For. 69:25-26.

Halls, L. K., J. D. McCarty, and H. V. Wiant. 1970. Relative browsing of 16 species by white-tailed deer. J. of Range Manage. 23(2):146-147.

Halls, L. K., and W. B. Homesley. 1966. Stand composition in a mature pine-hardwood forest of southeastern Texas. J. of For. 64:170-174.

Halls, L. K. and T. H. Ripley. 1961. Deer browse plants of southern forests. U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., New Orleans, La., and Southeast. For. Exp. Stn., Asheville, N.C.; in coop. with For. Game Res. Comm., Southeast. Sect. of the Wildlife Soc. 78 p.

Harlow, R. F., P. A. Schrauder, and M. E. Seehorn. 1975. Deer browse resources of the Oconee National Forest. U.S. Dep. Agric. For. Serv., Res. Pap. SE-137. 16 p.

Harlow, R. F., D. D. Strode, and L. M. Oliphant. 1966. Timber and deer thrive under even-aged hardwood management. South. Lumberman 213(2656):118-120.

Harris, W. F., R. A. Goldstein, and G. S. Henderson. 1973. Analysis of forest biomass pools, annual primary production and turnover of biomass for a mixed deciduous forest watershed. *In* IUFRO Biomass Studies, H. E. Young, ed. Univ. Maine, Orono. P. 43-64.

Hastings, E. F. 1966. Yield and chemical analyses of fruit produced by selected deer-browse plants in a loblolly-shortleaf pine-hardwood forest. Ph.D. dissertation, La. State Univ., Baton Rouge. 230 p.

Healy, W. M. 1971. Forage preferences of tame deer in a northwest Pennsylvania clearcutting. The J. of Wildlife Manage. 35(4):717-723.

Heath, G. W. and M. K. Arnold. 1966. Studies in leaf-litter breakdown. II. Breakdown rate of "sun" and "shade" leaves. Pedobiologia 6:238-243.

Heeren, R. D. 1969. Seed production of southern red oaks on a mineral pocosin in coastal North Carolina. Woodlands Res. Note No. 23, Union Camp Corp., Franklin, N.C. 2 p.

Helvey, J. D. 1964. Rainfall interception by hardwood forest litter in the southern Appalachians. U.S. Dep. Agric. For. Serv., Res. Pap. SE-8. 8 p.

Horwitz, W., chairman and ed. 1965. Official methods of analysis of the Association of Official Agricultural Chemists. 10th ed. 957 p. Washington, D.C.: Assoc. Off. Agric. Chem.

Hough, W. A. 1969. Caloric value of some forest fuels of the southern United States. U.S. Dep. Agric. For. Serv., Res. Note SE-120. 6 p.

Jackson, L. W. R. 1967. Relation of leaf structure to shade tolerance of dicotyledonous tree species. For. Sci. 13:321-323.

Johnson, F. L. and P. G. Risser. 1974. Biomass, annual net primary production, and dynamics of six mineral elements in a post oak-blackjack oak forest. Ecol. 55:1246-1258.

Kearney, N. S., Jr. and F. T. Bonner. 1968. Sweetgum seed production on soils in central Mississippi. U.S. Dep. Agric. For. Serv. Res. Note SO-75. South. For. Exp. Stn., New Orleans. 2 p.

Keays, J. L. 1975. Full forest harvesting—the source of tomorrow's chips. Am. Pap. Ind., Mar. 1975, 4 p.

Keays, J. L. 1976. Foliage. Part I. Practical utilization of foliage. Appl. Polym. Symp. No. 28, pp. 445-464. New York, N.Y.: John Wiley & Sons, Inc.

Keays, J. L. and G. M. Barton. 1975. Recent advances in foliage utilization. West. For. Prod. Lab. Inf. Rep. VP-X-137, 94 p. Can. For. Serv., Vancouver, B.C. Can.

Kellison, R. C. 1967. A geographic variation study of yellow-poplar (*Liriodendron tulipifera* L.) within North Carolina. Tech. Rep. No. 33, 41 p. N. C. State Univ., Raleigh, N.C.

King, T. R., and H. E. McClure. 1944. Chemical composition of some American wild feedstuffs. J. Agric. Res. 69:33-46.

Knierim, P. G., K. L. Carvell, and J. D. Gill. 1971. Browse in thinned oak and cove hardwood stands. J. Wildl. Manage. 35(1):163-168.

Kozlowski, T. T. 1971. Growth and development of trees. Vol. II. Cambial growth, root growth, and reproductive growth 514 p. N.Y.: Academic Press, Inc.

Kozlowski, T. T. and J. J. Clausen. 1965. Changes in moisture contents and dry weights of buds and leaves of forest trees. Bot. Gaz. 126(1):20-26.

Kozlowski, T. T. and W. J. Davies. 1975. Control of water loss in shade trees. J. of Arboric. 1(5):81-90.

Kozlowski, T. T. W. J. Davies, and S. D. Carlson. 1974. Transpiration rates of *Fraxinus americana* and *Acer saccharum* leaves. Can. J. of For. Res. 4:259-267.

Lay, D. W. 1962. The concentration of fruit crops to range carrying capacity. Paper presented at Amer. Soc. Range Manage., Corpus Christi, Tex., Jan. 25. 6 p.

Loomis, R. M. 1975. Annual changes in forest floor weights under a southeast Missouri oak stand. U.S. Dep. Agric. For. Serv., Res. Note NC-184. 3 p.

Loomis, R. M. 1977. Wildfire effects on an oak-hickory forest in southeast Missouri. U.S. Dep. Agric. For. Serv., Res. Note NC-219. 4 p.

Lunt, H. A. 1955. Effects of weathering upon dry matter and composition of hardwood leaves. J. For. 33:607-609.

McHargue, J. S., and W. R. Roy. 1932. Mineral and nitrogen content of the leaves of some forest trees at different times in the growing season. Bot. Gaz. 94:381-393.

McVickar, J. A. 1949. Composition of white oak leaves in Illinois as influenced by soil type and soil composition. Soil Sci. 68:317-328.

Maddocks, J. 1976. Hardwoods & wildlife—here today, here tomorrow. Part I: manage the hardwoods. Part II: pine trees for wildlife. For. & People 26(2):10-13, 32-36; 14-16, 44-45.

Madgwick, H. A. I. and D. F. Olson. 1974. Leaf area index and volume growth in thinned stands of *Liriodendron tulipifera* L. J. Appl. Ecol. 11:575-580.

Matschke, G. H., K. M. Barth, and R. L. Murphree. 1973. Digestion of crude protein in white oak acorns by European wild hogs and Pitman-Moore miniature hogs. J. of the Tenn. Acad. of Sci. 48(3):85-87.

Metz, L. J. 1952. Weight and nitrogen and calcium content of the annual litter fall of forests in the South Carolina Piedmont. Proc. Soil Sci. Soc. Am. 16(1):38-41.

Metz, L. J. 1954. Forest floor in the Piedmont region of South Carolina. Proc. Soil Sci. Soc. Am. 18:335-338.

Minckler, L. S. and S. F. Gingrich. 1970. Relation of crown width to tree diameter in some upland hardwood stands of southern Illinois U.S. Dep. Agric. For. Serv., Res. Note NC-99. 4 p.

Monk, C. D., G. I. Child, and S. A. Nicholson. 1970. Biomass, litter and leaf surface area estimates of an oak-hickory forest. OIKOS 21:138-141.

Newhouse, M. E. and H. A. I. Madgwick. 1968. Comparative seedling growth of four hardwood species. For. Sci. 14:27-30.

Olson, D. F. 1971. Sampling leaf biomass in even-aged stands of yellow poplar (*Liriodendron tulipifera* L.) *In* Forest Biomass Studies, H. E. Young, ed., Univ. Maine, Orono, p. 115-122.

Olson, D. F., Jr. and S. G. Boyce. 1971. Factors affecting acorn production and germination and early growth of seedlings and seedling sprouts. *In* Oak symp. proc., p. 44-48. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Ovington, J. D. 1956. The composition of tree leaves. For. 29:22-28.

Pearson, H. A. and H. S. Sternitzke. 1976. Deer browse inventories in the Louisiana Coastal Plain. J. Wildl. Manage. 40(2):326-329.

Petrides, G. A., P. Parmalee, and J. E. Wood. 1953. Acorn production in east Texas. J. Wildl. Manage. 17(3):380-382.

Pirie, N. W. 1975. Leaf protein: A beneficiary of tribulation. Nature 253:239-241.

Pray, T. R. 1954. Foliar venation of angiosperms. I. Mature venation of Liriodendron. Amer. J. Bot. 41(8):663-670.

Pray, T. R. 1955. Foliar venation of angiosperms. II. Histogenesis of the venation of liriodendron. Amer. J. Bot. 42(1):18-27.

Reid, V. H. and P. D. Goodrum. 1957. Factors influencing the yield and wildlife use of acorns. *In* Special problems in southern forest management. proc. sixth annu. for. symp., pp. 46-79. Baton Rouge, La.: La. State Univ.

Reiners, W. A., and N. M. Reiners. 1970. Energy and nutrient dynamics of forest floors in three Minnesota forests. J. Ecol. 58:497-519.

Ribe, J. H. 1973. Puckerbrush weight tables. Misc. Rep. 152. Life Sci. and Agric. Exp. Stn., Univ. Maine, Orono. 92 p.

Rochow, J. J. 1974. Litter fall relations in a Missouri forest. Oikos 25(1):80-85.

Rothacher, J. S., F. E. Blow, and S. M. Potts. 1954. Estimating the quantity of tree foliage in oak stands in the Tennessee Valley. J. For. 52:169-173.

Schopmeyer, C. S., tech. coord. 1974. Seeds of woody plants in the United States. U.S. Dep. Agric., Agric. Handb. 450. 883 p. U.S. Govt. Print. Off., Washington, D.C.

Schuster, J. L. and L. K. Halls. 1962. Timber overstory determines deer forage in shortleaf-loblolly pine-hardwood forests. *In* Proc., Soc. of Amer. For., pp. 165-167.

Segelquist, C. A. and W. E. Green. 1968. Deer food yields in four Ozark forest types. J. Wildl. Manage. 32(2):330-337.

Segelquist, C. A. and R. E. Pennington. 1968. Deer browse in the Ouachita Forest in Oklahoma. J. Wildl. Manage. 32(3):623-626.

Segelquist, C. A., H. L. Short, F. D. Ward and R. G. Leonard. 1972. Quality of some winter deer forages in the Arkansas Ozarks. J. Wildl. Manage. 36(1):174-177.

Segelquist, C. A., F. D. Ward, and R. C. Leonard. 1969. Habitat-deer relations in two Ozark enclosures. J. Wildl. Manage. 33:511-520.

Shanks, R. E., and J. S. Olson. 1961. First-year breakdown of leaf litter in southern Appalachian forests. Sci. 134:194-195.

Sharp, W. M. 1958. Evaluating mast yields in the oaks. Pa. State Univ. Agric. Exp. Stn. Bull. 635, 22 p.

Sharp, W. M., and V. G. Sprague. 1967. Flowering and fruiting in the white oaks. Pistillate flowering, acorn development, weather, and yields. Ecology 48:243-251.

Shaw, S. P. 1971. Wildlife and oak management. *In* Oak symp. proc., p. 84-89. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Upper Darby, Pa.

Short, H. L. 1966. Effects of cellulose levels on the apparent digestibility of feeds eaten by mule deer. J. Wildl. Manage. 30(1):163-167.

Short, H. L. 1971. Forage digestibility and diet of deer on southern upland range. J. Wildl. Manage. 35(4)698-706.

Short, H. L. 1976. Composition and squirrel use of acorns of black and white oak groups. J. Wildl. Manage. 40(3):479-483.

Short, H. L., R. M. Blair, and E. A. Epps, Jr. 1975. Composition and digestibility of deer browse in southern forests. U.S. Dep. Agric. For. Serv., Res. Pap. SO-111. 10 p.

Short, H. L. and E. A. Epps, Jr. 1976. Nutrient quality and digestibility of seeds and fruits from southern forests. J. Wildl. Manage. 40(2):283-289.

Short, H. L., and E. A. Epps, Jr. 1977. Composition and digestibility of fruits and seeds from southern forests. Spec. Rep., U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., New Orleans, La.

Short, H. L. and J. C. Reagor. 1970. Cell wall-digestibility affects forage value of woody twigs. J. Wildl. Manage. 34(4):964-967.

Sims, I. H. 1932. Litter deposition and accumulation in the pine-oak type of the southern Appalachians. J. For. 30:90-91.

Smith, C. C. and D. Follmer. 1972. Food preferences of squirrels. Ecol. 53(1):82-91.

Smith, R. F. 1967. The leaf dimorphism of *Liquidambar styraciflua* L. Amer. Midl. Nat. 77(1):42-50.

Sollins, P., and R. M. Anderson (ed.). 1971. Dry-weight and other data for trees and woody shrubs of the southeastern United States. Ecolog. Sci. Div., Publ. No. 407, ORNL-IBP-71-6. 80 p.

Stanton, W. M. 1976. Why leaves change from green to glory. Agric. Ext. Serv. For. Resour. Notes. 2 p. Raleigh, N.C.: N.C. State.

Stone, D. E. 1961. Ploidal level and stomatal size in the American hickories. Brittonia 13:293-302.

Stransky, J. J. and L. K. Halls. 1967. Timber and game food relations in pine-hardwood forests of the southern United States. *In* 14th Congr. Pap., Int. Union For. Res. Organ. 7:208-217.

Stransky, J. J. and L. K. Halls, and E. S. Nixon. 1976. Plants following timber harvest: importance to songbirds. Tx. For. Pap. No. 28. 13 p. Nacogdoches, Tx.: Stephen F. Austin State Univ.

Stransky, J. J., and D. Richardson. 1977. Fruiting of browse plants affected by pine site preparation in east Texas. *In* Proc., 33rd Ann. Conf. Southeast. Assoc. Fish and Wildl. Ag. (Oct. 9-12. San Antonio.) p. 5-7.

Switzer, G. L., L. E. Nelson, and L. E. Hinesley. 1978. Effects of utilization on nutrient regimes and site productivity. *In* Complete tree utilization of southern pine: symp. proc., New Orleans, La., April 17-19. C. W. McMillin, ed. For. Prod. Res. Soc., Madison, Wis., p. 91-102.

Thor, E. and G. M. Nichols. 1973. Some effects of fires on litter, soil, and hardwood regeneration. *In* Proc. annu. tall timbers fire ecol. conf., pp. 317-329.

Tippin, T. (ed.). 1978. Principles of maintaining productivity on prepared sites. Symp. Proc., March 21-22, Jackson, Miss., 171 p. U.S. Dep. Agric. For. Serv., South. For. Exp. Stn., New Orleans.

Tryon, E. H., and K. L. Carvell. 1962. Acorn production and damage. West Va. Agric. Exp. Stn., Bull. 466T. 18 p. West Va. Univ., Morgantown.

U.S. Department of Agriculture, Forest Service. 1951. Leaf analysis of white oak and its relation to site quality. Annual Rep. 1950: 27-28. Cent. States For. Exp. Stn.

U.S. Department of Agriculture, Forest Service, 1969. Wildlife habitat improvement handbook. U.S. Dep. Agric. For. Serv., Washingotn, D.C.

Ulliman, J. J., and C. R. Hatch 1978. Test of an electronic planimeter. J. For. 76:346-347.

Vidrine, C. G., and G. E. Woodson. 1982. Bulk densities of materials from selected pine-site hardwoods. For. Prod. J. 32(7): 21-24.

Wainio, W. W., and E. B. Forbes. 1941. The chemical composition of forest fruits and nuts from Pennsylvania. J. Agric. Res. 62:527-635.

Wargo, P. M. 1978. Correlations of leaf area with length and width measurements of leaves of black oak, white oak, and sugar maple. U.S. Dep. Agric. For. Serv., Res. Note NE-256. 3 p.

White, D. P. and R. F. Finn. 1964. Frost damage in a tulip poplar plantation as related to foliar potassium content. Pap. of the Mich. Acad. of Sci., Arts, and Letters 49:75-80.

Whittaker, R. H., N. Cohen, and J. S. Olson. 1963. Net production relations of three tree species at Oak Ridge, Tennessee. Ecol. 44:806-810.

Whittaker, R. H., and G. M. Woodwell. 1969. Structure, production, and diversity of the oak-pine forest at Brookhaven, New York. J. Ecol. 57:155-174.

Witkamp, M. and J. S. Olson. 1963. Breakdown of confined and nonconfined oak litter. Oikos 14(2):138-147.

Wolters, G. L., A. Martin, Jr. and W. P. Clary. 1977. Timber, browse, and herbage on selected loblolly-shortleaf pine-hardwood forest stands. U.S. Dep. Agric. For. Serv., Res. Note SO-223. 9 p.

Wolters, G. L., and A. T. Wilhite, Jr. 1974. Loblolly-shortleaf pine-hardwood range. *In* Range resources of the South. p. 20-23. Ga. Agric. Exp. Stn. Bull. N.S. 9.

Woods, D. B., and N. C. Turner. 1971. Stomatal response to changing light by four tree species of varying shade tolerance. New Phytol. 70:77-84.

Woodwell, G. M. 1974. Variation in the nutrient content of leaves of *Quercus alba*, *Quercus coccinea*, and *Pinus rigida* in the Brookhaven forest from bud-break to abscission. Am. J. Bot. 61(7):749-753.

Woodwell, G. M., R. H. Whittaker, and R. A. Houghton. 1975. Nutrient concentrations in plants in the Brookhaven oak-pine forest. Ecol. 56(2):318-332.

Young, H. E., and P. M. Carpenter. 1967. Weight, nutrient element, and productivity studies of seedlings and saplings of eight tree species in natural ecosystems. Tech. Bull. 28, Maine Agric. Exp. Stn., Univ. Maine, Orono. 39 p.

Zavitovski, J., J. G. Isebrands, and T. R. Crow. 1974. Application of growth analysis in forest biomass studies. *In* Proc. of the third North American forest biology workshop, pp. 196-226. C. P. P. Reid and G. H. Fechner, compilers and eds. Soc. of Am. For., Colo. State Univ., and U.S. Dep. Agric. For. Serv., Rocky Mt. For. Exp. Stn., Ft. Colling, Colo.